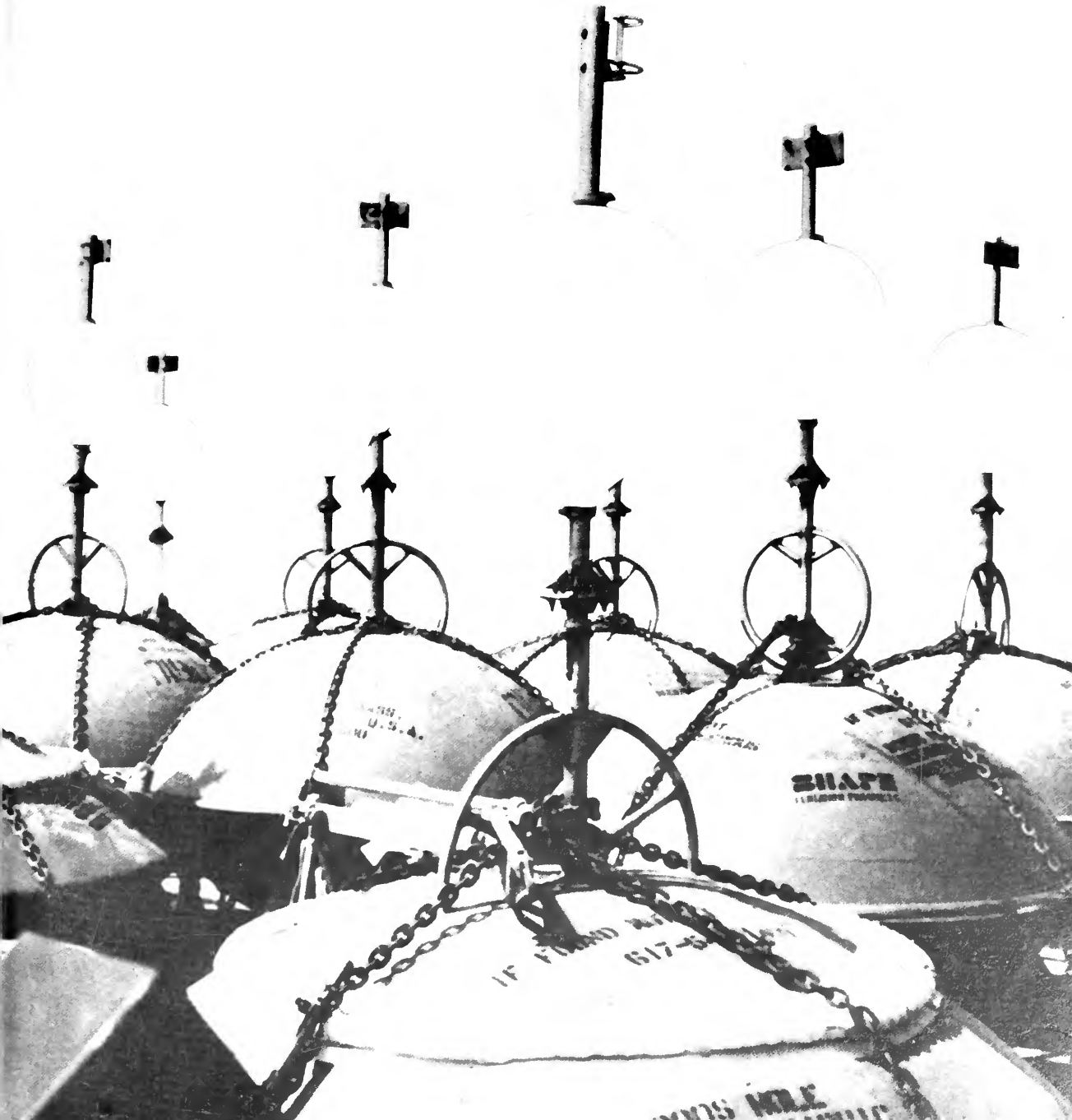
Oceanus

Volume 25, Number 2, Summer 1982



Oceanus®

The Magazine of Marine Science and Policy

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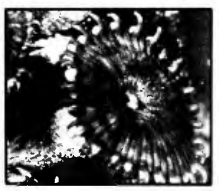

FRONT COVER: Foam subsurface floats on the aft deck of the research vessel *Oceanus* after an acoustic tomography experiment. The balloons at the top of the floats serve as aids for visual spotting (see page 12). (Photo by Paul Boutin, WHOI)
BACK COVER: Recovering a subsurface float. (Photo by Joseph Kiebala, Jr., WHOI)

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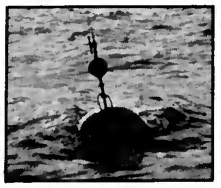

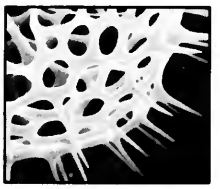

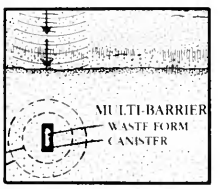

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The Newest Federalism and Coastal Areas

by Thomas D. Galloway and Dennis Nixon

My administration is committed heart and soul to returning authority, responsibility, and flexibility to state and local government . . .

President Ronald Reagan

The election of Ronald Reagan in 1980 was more than a demand by the people for temporary relief from their economic hardships. It was a mandate for the fundamental changes that are necessary to recapture the spirit and vigor and optimism that once was America's hallmark.

A revitalized federalism is a crucial part of the fundamental change.

Senator Paul Laxalt
Chairman, Presidential Advisory Committee on Federalism

What does the Reagan Administration's new federalism mean for coastal states, communities, and resources? Although we cannot predict the future, there are many important issues and potential impact areas that require the attention of individuals concerned with coastal affairs. Before addressing these, however, it is useful to define the major principles of the new federalism and to suggest how these principles do or do not match up with the notion of federalism embedded in the coastal management experience of the last 10 years.

The Newest Federalism

In its view of federalism, the Reagan Administration departs significantly from those of the last 50 years. Whereas the New Deal period of the 1930s and 1940s marked an increase in the involvement of the federal government in local affairs, the President's "New Beginning" marks a significant movement in the opposite direction.

The central theme of the new federalism is to curb the expansion of the federal government while returning certain powers and responsibilities to state and local governments. In a phrase, the new federalism seeks to help state and local governments "regain their autonomy" in the federal system. In more specific terms, the new federalism maintains the following major principles: substitute federal block grants for single-purpose categorical grants so that states can set their own spending priorities; move federal regulatory authority to state and local levels wherever possible; and, for the purpose of carrying out their new responsibilities, replace federal funding by creating new revenue sources (or transferring old ones) for state and local governments.

These principles can be contrasted to those incorporated by previous administrations. It is inappropriate to view the expansion of the federal government as simply the logical extension of the New Deal. Yet the views of federalism advanced by succeeding administrations have been at their core more alike than different. The consensual theme was that of "cooperative federalism," the sharing of functions between federal, state, and local governments. Examples include: Lyndon Johnson's "Creative Federalism," posing innovative coordination of intergovernmental resources; Richard Nixon's "New Federalism," which provided the conceptual bases for much of Reagan's "New Federalism;" and Jimmy Carter's "New Partnership Federalism," holding promise not only for collaboration among levels of government, but also between the public and private sectors. All of these administrations, including the Nixon Administration, promoted intergovernmental sharing with an active federal role in many areas of subnational affairs.

Regardless of labels, the general principles underlying the recent history of federalism have been those recommended in 1955 by the Advisory

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Without federal funding, programs that presently help communities evaluate proposed development projects and cope with the results will either vanish or shrink. Pictured at left is the encroachment of a housing development on a Long Island, N.Y., bay. (Photo by Robert Perron)

Commission on Intergovernmental Relations (ACIR). In contrast to the principles of the new federalism, these recommendations argue for federal intrusion into state or local affairs in one or more of the following situations: "1) when the national government is the only agency that can summon the resources needed for an activity; 2) when the activity cannot be handled within the geographic and jurisdictional limits of smaller governmental units; 3) when the activity requires nationwide conformity of policy that cannot be achieved by interstate action; 4) when a state, through action or inaction, does injury to the people of other states; and 5) when states fail to respect or to protect basic political and civil rights that apply throughout the United States." Partially as a result of these principles, past administrations have been cautious in making concrete separations of authority between federal, state, and local governments. This is clearly not the case today.

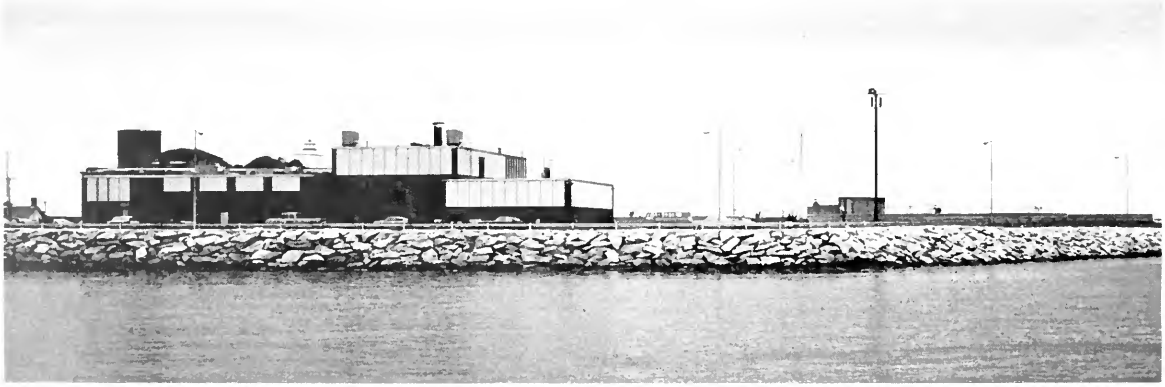
Already, the Reagan Administration has taken several steps to implement its ideas: 1) it has created a structure for advancing its notion of the new federalism — The Presidential Advisory Committee on Federalism, chaired by the President's longtime friend and advisor, Senator Paul Laxalt (Nevada); 2) it has appointed Interior Secretary James Watt as chairman of the ACIR; 3) it has, in the Omnibus Budget Reconciliation Act of 1981, authorized nine block grants, displacing 77 previous categorical programs; 4) it has created the Presidential Task Force on Regulatory Relief, chaired by Vice President George Bush; and 5) it has presented to Congress, in the President's State of the Union Message in January of this year, a plan for exchanging responsibility for Medicare and welfare programs between federal and state governments, for creating a trust fund financed by excise taxes to assist the states in assuming what are now federal responsibilities, and for surrendering more than 40 federal grant programs to the states by 1988. However, what may appear simple at the general level often becomes quite complex on closer inspection. This is true in the case of coastal programs.

The Impact on the States

The federal Coastal Zone Management Act of 1972 contains elements of both the "old" and the "new" federalism. Like the "old" federalism, it provides for concurrent federal-state jurisdiction over coastal areas and promotes greater federal involvement in areas previously limited to state and local responsibility, such as land use control. But the Act also took a "new" approach by providing coastal states with unprecedented influence over some federal actions.

Major issues for individuals concerned with the future of coastal management are: What will constitute the national interest in coastal areas? How will the federal government manifest this interest (or disinterest) in the 1980s? Will such interests be restricted to national security issues, excluding energy, recreation, transportation, and projects with regional effects? Under conditions of the surrender of federal responsibilities, will or can coastal programs be maintained by the states?

Under the newest federalism, state response to coastal issues must be viewed within a framework of priorities competing for scarce resources. Because most states are experiencing their own revenue shortfalls in addition to the reductions in federal aid that have already taken effect, pressures on state spending have increased dramatically. In



Because of operational and design problems, this sewage treatment plant in New Bedford, Massachusetts, is catching only a fraction of the pollutants it is required to remove by federal law. In violation of its Environmental Protection Agency permit for the last two years, the plant needs modifications that the coastal city says it cannot afford. Federal funds that have helped communities correct such problems in the past are drying up. As the debate over a solution continues, the city's wastewater, high in toxic chemicals and heavy metals from local industry, flows into New Bedford harbor. Many other coastal cities have similar problems. (Photo courtesy of Massachusetts Office of Coastal Zone Management)

addition, under a block-grant system, priorities will differ from state to state and many policy areas previously imbued with "national interest" by Congress will not be seen as highly important by state legislatures. With increased fiscal burdens, states will have limited options: raise taxes, transfer programs to the private sector, or curtail programs. Exactly what becomes of the planning for and management of coastal resources will likely be a function of special interest advocacy as it manifests itself in the various states. In other words, the impact of the new federalism will be significant.

Cuts in several federal programs will have a direct impact on coastal states and communities. The most obvious example is the proposed elimination of program management grants to the states under the Coastal Zone Management Act. States have typically used these funds to plan and regulate coastal activities. When a conflict arises over a proposed use of the coastal zone, the program staff members can independently assess the project's features and determine whether it conforms to that state's management plan and policies. Without program management funding, decision-makers would have to do without this independent source of information. Multiple-use conflicts would probably become increasingly adversary in nature, with information supplied only by the proponents and opponents of a new use. It is unlikely that the public's interest would be represented fully unless private groups fill the void.

Also slated for termination is the Coastal Energy Impact Program, which has provided grants and loans to states for the mitigation of the adverse effects of coastal energy development, particularly the drilling for oil on the Outer Continental Shelf (OCS). Drilling is sure to increase; the Interior Department's five-year leasing schedule calls for close to a billion acres of federally owned offshore land to be offered for lease. Although the drilling is not within state boundaries, its impacts certainly can be. A marsh can be damaged by dredging for a pipeline, for instance, or a rapid influx of oil workers can strain a community's facilities. There are other precedents for compensating the states. Federal laws governing the leasing of federal land for timber harvesting, livestock grazing, and mining provide that a portion of the lease receipts must be shared with the affected state.

Another important concern for coastal states and communities is the virtual dismantling of the Environmental Protection Agency (EPA). President Reagan initially threatened to eliminate EPA's Construction Grants Program, which provides aid to communities for the construction of sewage treatment plants to meet the standards established by the federal Clean Water Act. A coalition of 55 nationwide environmental groups, states, and local governments succeeded in keeping the program alive for another year, but at a reduced level of

A boating safety inspection. If funding for state safety patrols is reduced, more responsibility for such patrols will fall to the U.S. Coast Guard, which is increasingly hard-pressed for funds itself. (Photo courtesy of U.S. Coast Guard)

funding. This decrease will mean an increased burden on state and local governments struggling to maintain and improve their sewage treatment systems.

The proposed elimination of the Economic Development Administration (EDA) could have a major impact on coastal communities seeking to revitalize urban waterfronts and create jobs. The Administration refers to the EDA as a "political tool," but it has been the source of many important fishery-development projects. For example, an EDA grant was the cornerstone of a proposed joint venture between the United States and Spain for squid processing in Newport, Rhode Island. Site problems have delayed the proposal, but it would not have been made at all without EDA assistance.

Further reductions in U.S. Coast Guard funding may create a void that state governments will have to consider — particularly in the area of boating safety. The Coast Guard's Office of Boating Safety, which funds state boating programs with revenues from the federal motorboat fuel tax (4 cents a gallon), is the subject of a dispute between Congress and the Administration. If the Administration succeeds in blocking funds for the program, states will either have to eliminate their marine safety patrols or devise another way of financing them.

Coastal states will lose another important source of research and information if the proposed cuts in the budget of the National Marine Fisheries Service (NMFS) are approved. NMFS programs that directly benefit coastal states and are scheduled to

Termination of federal subsidies to American shipyards could make it harder for them to compete with foreign builders. (Photo courtesy of General Dynamics Corporation)

be terminated are: anadromous fisheries grants; commercial fisheries research and development grants; fisheries development grants; aquaculture research and development; and the salmon vessel buy-back program on the West Coast. The Administration's position is that all of these programs should be financed by either state governments or the private sector.

The National Sea Grant Program, which funds marine research, advisory services, and marine education at universities, also was proposed for termination. Congress has since reauthorized this program for Fiscal Year 1982, but a battle over future funding is likely.

Finally, the proposed termination of the Maritime Administration's Construction Differential Subsidy Program could deliver a major setback to American Shipyards, which have relied on this program to help them compete with foreign builders. On the other hand, the proposed increase in naval shipbuilding may provide enough income to keep the commercial shipyards "afloat."

Just as the diminution of federal interest in these areas poses new and significant challenges for state governments, local governments in coastal areas also will be affected.

The Impact on Coastal Communities

Quite aside from impacts generated by the new federalism, coastal communities are already hard-pressed from other directions. Population migration to coastal communities is increasing. Fiscal pressures resulting from high inflation are aggravated by the reliance on a revenue source — the property tax — that is highly sensitive to the construction slowdown brought on by the recession. Many localities have already found it necessary to under-maintain their capital facilities in order to meet more pressing budgetary demands. And assistance from state governments is dwindling. Federal funding cutbacks intensify these problems.

Some specific areas for which coastal communities may have to look inward for help include: urban waterfront revitalization; urban economic development; capital facility investment; public access to waterfronts and beaches; and environmental protection. Yet with the atmosphere of fiscal stringency, local governments will be under pressure to return to the basics (police protection, fire protection, solid waste disposal). There will be little or no local reserve left to continue the federally aided initiatives of the 1970s.

The larger view of the new federalism's impact on coastal communities is twofold. First, a number of previous federal initiatives that promoted growth probably will be eliminated. These include federal subsidies and direct federal investments in highways and capital structure, such as water and sewer grants and loans. Federal subsidies traditionally have encouraged development on barrier beaches. The government not only provides low-interest loans for the construction of new homes, but hands over more money for the bridges needed to reach them, the jetties needed to slow down the natural shifting of the sand, and the cut-rate flood insurance and disaster aid that stimulate rebuilding between storms. But none of these subsidies will apply to new construction on undeveloped barriers if Congress passes the Coastal Barrier Resources Bill (H.R. 3253 and S. 1018), which the White House has not opposed. The flood insurance program has already been cut back; no policies will be issued for barrier island homes built after October of 1983.

Second, programs that help communities cope with their growth problems also will be eliminated or diminished, such as the Comprehensive Planning Assistance Program. Since it is likely that coastal communities will continue to feel growth problems, despite federal withdrawal from "growth inducing" investments, it is likely that in the 1980s these communities will find their ability to meet their problems more constrained than assisted by the changes prescribed by the new federalism. Their future, of

Waterfront Park in Boston —an example of urban waterfront revitalization. (Photo courtesy of Massachusetts Office of Coastal Zone Management)

A variety of federal programs has long promoted building on barrier beaches, but some of these subsidies may soon end. Pictured here is the south shore of Long Island, N.Y. (Photo by Robert Perron)

Cut-rate flood insurance and disaster aid provided by the federal government encourage the owners of beachfront homes to rebuild between storms. But these subsidies will not apply to future homes built on undeveloped barrier beaches if Congress passes the Coastal Barrier Resources Bill. (Photo courtesy of National Oceanic and Atmospheric Administration)

course, is almost totally dependent on the actions of state governments.

In the previous contexts, attention has been focused on conventional governmental relationships. Yet the willingness and the capacities of states and localities to continue efforts in coastal resource management are at best uncertain. It is quite plausible that state and local governments may decide that coastal resource management calls for new institutional forms and alternative financial support mechanisms.

Alternative Arrangements

If the proposed budget cuts and intergovernmental changes are accomplished, what is left of government programs and services will have to be organized and financed in a new way. There is no simple solution to the funding dilemma. What is likely to sift out of the dozens of proposals and counterproposals is a combination of three basic elements: user fees, revenue sharing, and private-sector financing.

User fees are the solution most often recommended by the Reagan Administration — getting what you pay for, and paying for what you get. The concept has great appeal for specific government activities, but has limitations as a universal funding solution. The role of user fees in coastal and maritime programs will be hotly debated in the months ahead.

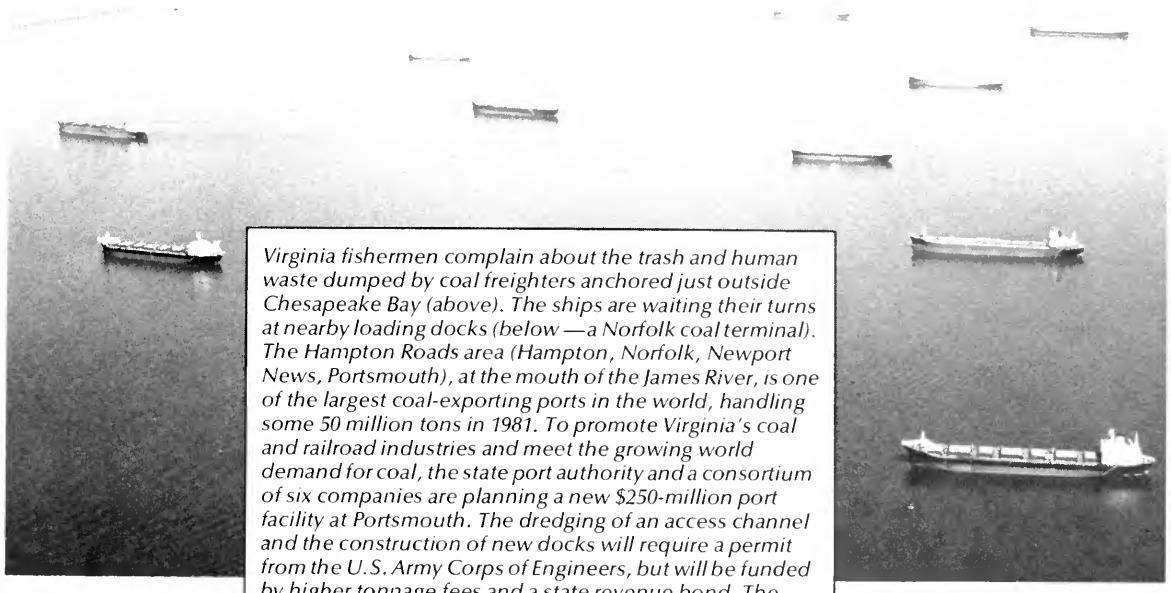
In some cases, user fees are already in effect but represent only a small percentage of the actual cost to the responsible government agency. For example, permit fees required for development projects by the U.S. Army Corps of Engineers and by state coastal agencies would have to be increased enormously to fully meet the investigative and administrative costs associated with permit approval. Making the permit process more expensive might not enhance coastal development but certainly would help make the system self-supporting.

Sewer use fees also have been used for many years but do not normally meet the full cost of plant operation. A recent General Accounting Office (GAO) report found that only half of the 36 municipal wastewater treatment plants the GAO reviewed in 10 states were raising sufficient funds from their user charges to cover operation and maintenance costs. Even more disturbing is that only three of the 36 municipalities were setting aside funds to replace old treatment plants. A higher sewer use fee might have the dual function of raising additional revenues and promoting conservation. A determined conservation effort would slow the need for additional capital improvements.

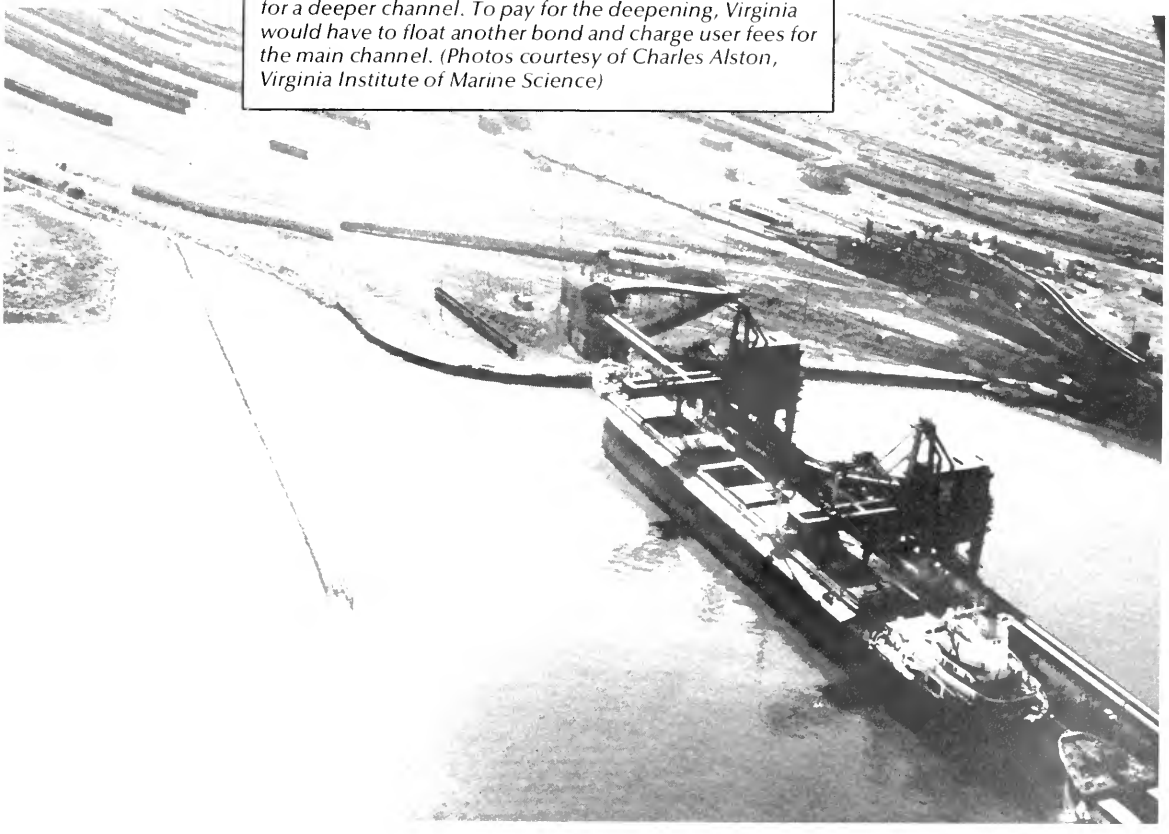
A new user fee of between $50 and $600 a year has been proposed by the federal government to recoup the Coast Guard's costs of providing navigational services to recreational boaters. On top of that might be an increase in state registration fees corresponding to the decrease in the federal boating safety grant program. The combined effect will make boating more expensive and perhaps constrain growth in that industry.

Commercial vessels would be required to pay up to $20,000 a year under the same Coast Guard user fee proposal. Pier space provided by state and local governments often has been supplied at or below cost to encourage the use of a particular port facility. Since federal money for port improvement projects probably will be terminated or greatly reduced, it appears certain that state and local wharfage charges will have to be substantially increased.

Recreational shoreline users are the final class of individuals who may be asked to pay more for services traditionally supplied by the state with tax revenues. A saltwater fisherman's license has been proposed to control the number of participating anglers and to raise funds for recreational fisheries research. User fees at beaches owned by local governments have risen so much that they are now significant revenue sources supporting other government activities.



Virginia fishermen complain about the trash and human waste dumped by coal freighters anchored just outside Chesapeake Bay (above). The ships are waiting their turns at nearby loading docks (below—a Norfolk coal terminal). The Hampton Roads area (Hampton, Norfolk, Newport News, Portsmouth), at the mouth of the James River, is one of the largest coal-exporting ports in the world, handling some 50 million tons in 1981. To promote Virginia's coal and railroad industries and meet the growing world demand for coal, the state port authority and a consortium of six companies are planning a new $250-million port facility at Portsmouth. The dredging of an access channel and the construction of new docks will require a permit from the U.S. Army Corps of Engineers, but will be funded by higher tonnage fees and a state revenue bond. The project will be more profitable if the main channel is deepened to allow access by deeper-draft ships. In the past, the federal government has paid for the deepening and maintenance of main harbor channels, but Congress may soon end that tradition. A Senate bill supported by the Reagan Administration would make states pay for all such dredging in the future, except when there is a military need for a deeper channel. To pay for the deepening, Virginia would have to float another bond and charge user fees for the main channel. (Photos courtesy of Charles Alston, Virginia Institute of Marine Science)



A saltwater fisherman's license has been proposed as one possible source of funds that could be used by states to support recreational fisheries research. Federal programs for such research are slated for reduction or termination. (Photo courtesy of Massachusetts Office of Coastal Zone Management)

A second major financing mechanism, Outer Continental Shelf (OCS) revenue sharing, has been proposed. By allowing states to share in revenues from the leasing of offshore drilling tracts to oil companies, the plan would provide enough money to preserve existing coastal programs. The House Subcommittee on Oceanography has already approved H.R. 5543, which would establish an Ocean and Coastal Resources Management and Development Fund based on a contribution of 10 percent of the increase in revenues from the Outer Continental Shelf from fiscal year 1982, up to $300 million. The fund would be used to continue the Sea Grant program, the Coastal Energy Impact Program, certain state fishery programs, and marine resource management programs. The earmarking of funds specifically for coastal programs has made the bill quite controversial, but its supporters believe that it may be the only way to get the various programs funded.

Finally, private-sector financing is an alternative supported by the Reagan Administration

as part of its "voluntarism" approach to social problems. When a difficult coastal issue appears, the White House says, private funds should be made available to help solve it. The role of foundations is important, but of course limited by the sheer volume of new problems.

Although they usually cannot be more than a subsidiary source of funds, foundations sometimes can "save the day" in marine resource management conflicts. For example, two years ago The Nature Conservancy purchased the pristine northern third of Prudence Island, in Rhode Island's Narragansett Bay, just in time to keep it from becoming the site of a casino, a resort, or an oil refinery. Government funds already had been earmarked to purchase the parcel for a local park system, but red tape delayed the transaction and the impatient owner was about to take another offer. When the funds finally came through more than six months later, the Conservancy got its money back.

Both nonprofit organizations and special-purpose governmental units are likely to play increasingly important roles as substitutes for general-purpose governments in coastal resource management. Both types of organization have been evident in this area in the 1960s and 1970s. Examples extend from a variety of environmental nonprofit organizations to specific port authority districts and areawide governmental organizations, ranging from the Bay Area Conservation District in California to the Narragansett Bay Water Quality Commission in Rhode Island. However, nonprofit organizations are not likely to enjoy the special relationships with the federal government that they enjoyed in recent years.

Regardless of the organizational or financial arrangement, important public interest questions are raised. The two most important concerns are: to what extent can or will the organizational alternatives be politically accountable, and to what extent will financial alternatives be exclusive or inclusive relative to the publics served? Decentralization and deregulation pose serious tradeoffs in both accountability and equity for coastal resource users.

If Congress restores many of the Administration's proposed cuts in coastal programs, one possible source of funding would be revenues from the leasing of offshore drilling tracts. (Photo courtesy of American Petroleum Institute)

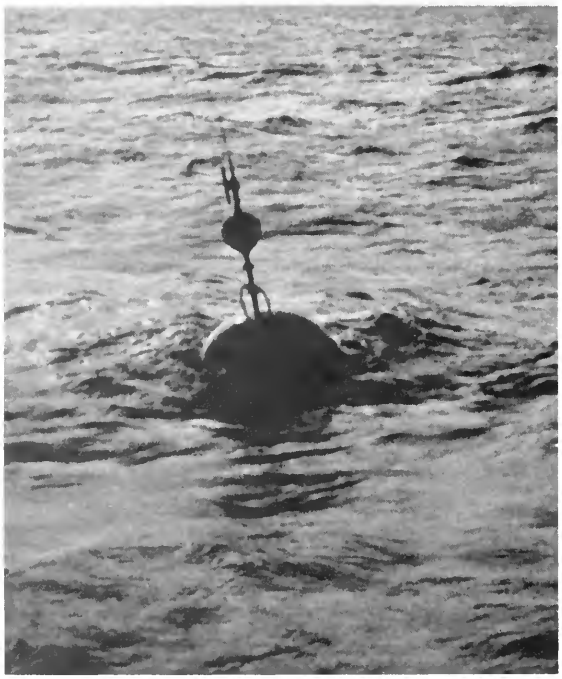
Summing Up

This article has defined the meaning of the new federalism for coastal resource planning and management, and has suggested concrete areas in which the impact may be felt. The new federalism departs substantially from the federalist concepts of the last 50 years. If fully implemented, it forbodes dramatic changes in coastal resource management. Implementation will be the subject of debate in the months and years to come.

Unfortunately, as fiscal pressures occupy the public agendas of most states and localities, one can envision the playing out of special-interest politics, leading to a greater privatization of coastal resources, uneven treatment of coastal issues among the states, and the general diminution of coastal resources as a policy issue. To minimize these possibilities, a measure of continued national interest in coastal affairs is required.

Thomas D. Galloway, a Professor, is Director of the Graduate Program in Community Planning and Area Development at the University of Rhode Island in Kingston, R.I. Dennis Nixon, an Assistant Professor, is Coordinator of the Graduate Program in Marine Affairs at the same university.

OCEAN ACOUSTIC



A subsurface float prior to recovery. (Photo by George Hampson, WHOI)

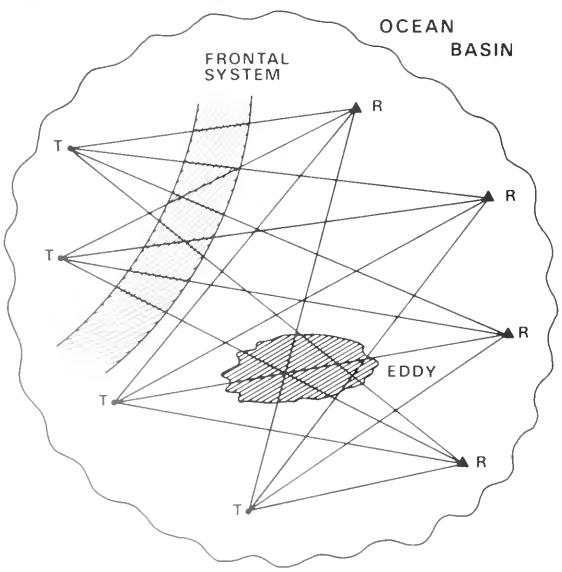


Figure 1. The principle of ocean acoustic tomography, showing transmission between multiple acoustic transmitters (T) and receivers (R).

by Robert C. Spindel

Scientists have developed a promising new technique of ocean measurement based on the transmission of sound beneath the sea. The technique is similar to one used in medicine called tomography—a method of observing the interior of an object by transmitting energy through it. "Tomo" derives from the Greek word *tomos*, meaning section or slice; a tomogram is a picture of a slice. Many sections are used to reconstruct a three-dimensional image. The mathematical procedure that must be followed was first proposed in 1917 by the German mathematician Radon. Figure 1 shows how it can be applied to the ocean. Sound is transmitted along many transmitter-to-receiver paths and the details of the interior ocean are determined by observing distinct and different transmission effects along each path.

Tomography found early and widespread use in medicine. The CAT (Computer-Assisted Tomography) scan employs X-rays for imaging parts of the body, usually the brain. Sound at a pitch above the limit of human hearing, called ultrasound, is also used to form tomographic images of body structures. Similarly, ocean acoustic tomography uses underwater sound waves to produce a "picture" of the interior processes of the ocean. It is a technique that was proposed by two oceanographers: Walter Munk of the Scripps Institution of Oceanography and Carl Wunsch of the Massachusetts Institute of Technology. Munk had for some time been studying underwater sound and had been working with both theoretical and applied underwater acousticians. Wunsch had done extensive oceanographic analysis using mathematical techniques quite similar to those used in tomographic imaging. Together they formulated the notions that have been melded into a practical measuring tool.

The scientific motivation for this development lies in perceptions of ocean circulation that have evolved during the last several decades. The oceans are extraordinarily complex systems of circulating waters that have a wide variety of time and space scales. We have intense, swiftly flowing currents, such as the Gulf Stream, that maintain coherent structure for thousands of miles. We have large, slowly rotating gyres the size of the Sargasso Sea. We have warm and cold rings and eddies with diameters of hundreds of kilometers and circulating currents of several knots.

TOMOGRAPHY:

A New Measuring Tool

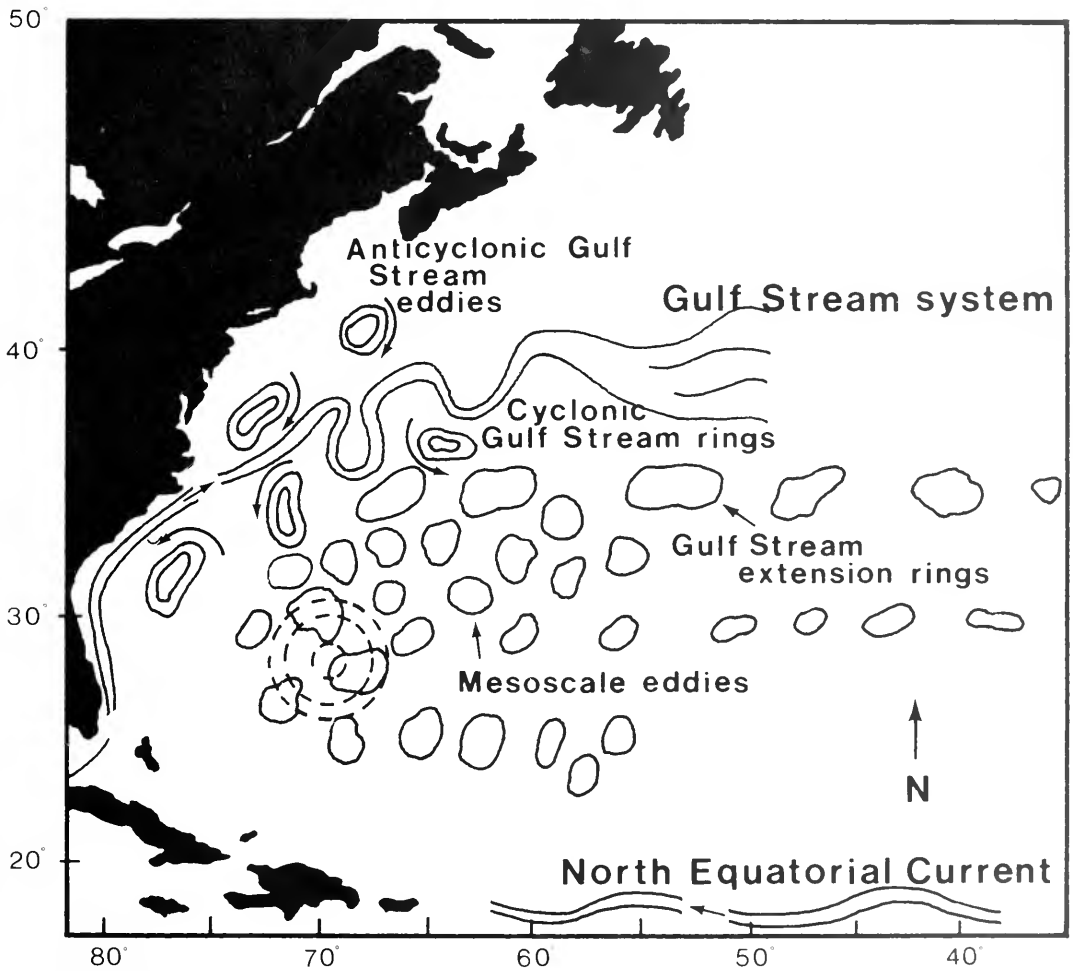


Figure 2. The variable ocean. (Drawing by Nancy Barnes, based on a map by William Simmons)

We have sharp upwellings like the Humboldt Current, which feeds the anchovies off the coast of Peru, and we have mixtures of nutrient-rich waters creating extremely fecund growing conditions, like those on Georges Bank off the New England coast. We also have oceanwide tidal currents and smaller currents associated with topographic effects near ocean boundaries. We have complicated mixing processes of saline and fresh water, of warm and cold water, and of deep and surface water. We have interactions with the atmosphere and mixing via wind-driven waves, and we have rifts, hot vents, and river runoffs. It seems that on whatever scale we observe the ocean—whether over decades, centuries, geologic epochs, or over the more human time scale of weeks, months, seasons, or years—we encounter processes of change and variability (Figure 2). Whether we observe on spatial scales approaching ocean basin size or scales the size of bubbles, we see fluctuation and change. The interaction among these and other processes creates complex patterns of ocean circulation.

These patterns have profound effects on our lives, yet they are only partially understood. One of the greatest obstacles to increased understanding is our inability to make proper observations. The seas are so vast, and their motions so ponderous, that we can only muster a fraction of the ships and other

Launching the bottom end of a mooring. Two acoustic releases precede the anchor. (Photo by George Hampson, WHOI)

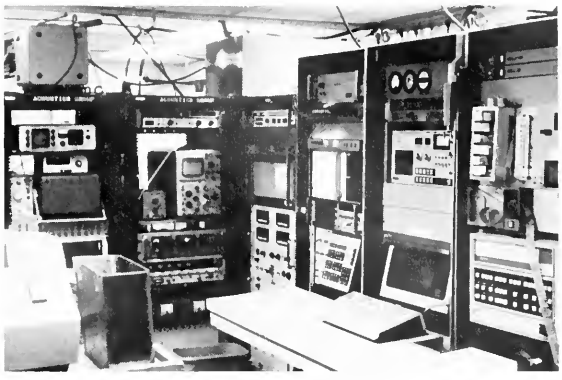
tools necessary to do the job, and we cannot commit those available to lengthy observation programs. It is difficult to predict how Gulf Stream meandering, for example, will affect the climate of the East Coast of the United States if we cannot observe the changing trajectory of the Stream. Long-term trends in North America's climate are strongly related to circulation patterns in the Pacific Ocean, yet we can predict climatic trends only if we have the necessary oceanic observations. The bountiful and lean years of the Peruvian anchovy fishery, the Atlantic and Pacific salmon fisheries, and other important protein sources also are strongly influenced by variations in ocean circulation. It is clear, then, that our understanding of the ocean depends on our capacity to observe it.

Until rather recently, most measures of ocean circulation consisted of mariner observations of set and drift with respect to wind and sea conditions. This led to an oceanic picture that showed only major surface currents in very crude fashion. It was thought, for example, that the Gulf Stream was very much like a strong river sweeping majestically from south of Florida, up the East Coast of the United States, and onward, with nary a wiggle across the Atlantic to Europe. The gradual addition of observations over many decades indicated that the Stream actually meandered, wandering in serpentine fashion. It was found that the meanders changed, that they varied from year to year, season to season. Improved navigation techniques allowed more accurate determination of ship set and drift and therefore more accurate estimates of surface currents. Devices were developed to measure currents beneath the surface, and it was found that we had only made a beginning in understanding ocean circulation. The ocean turned out to be even more complex as we probed deeper with moored current meters, ship-tracked neutrally buoyant pinging floats, and shore-triangulated acoustic float systems. We evolved a fairly detailed picture of complex, but still rather sedate, circulation. One might think of this as the steady state pattern of circulation.

During the last decade or two, we have come to realize that a complicated, almost random pattern of alteration and fluctuation is superimposed upon the steady state picture. The electronic revolution completely changed our method of observation, for the first time allowing measurement of currents and temperatures over long time periods. Departures from mean, steady-state flows were dramatically apparent. Estimates indicated that probably only 10 percent of the kinetic energy of the ocean was contained in the steady state. The remainder appeared to be in fluctuations. Most of this fluctuation energy appears to be associated with slow, mesoscale (medium-sized) eddies and meanderings extending from the sea surface to the bottom. With a typical radius on the order of 100 kilometers, these usually take a few months to pass by a given location in the ocean. Mariners were probably quite aware of mesoscale variability because their observations were inconsistent from year to year. However, one suspects that such changes were considered merely nuisances. It is only recently that we have begun to appreciate the importance of the mesoscale and its effects on our lives. In loose analogy with the atmosphere, one can think of the gross circulation

features of the ocean as the ocean climate, the long-term trends. Mesoscale features are the ocean's weather.

A group of researchers at the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography, the Massachusetts Institute of Technology, the University of Michigan, and the Miami laboratory of the National Oceanic and Atmospheric Administration have joined forces to develop ocean acoustic tomography into a viable scientific measuring tool. Principal investigators are Ted Birdsall (U. Mich.), Walter Munk and Peter Worcester (Scripps), Carl Wunsch (MIT), Dave Behringer (NOAA-AOML), and the author at Woods Hole. The group's initial efforts are concentrated on using tomography to observe the ocean mesoscale.



A shipboard laboratory equipped for acoustic experiments. (Photo by author)

Some Underwater Acoustics

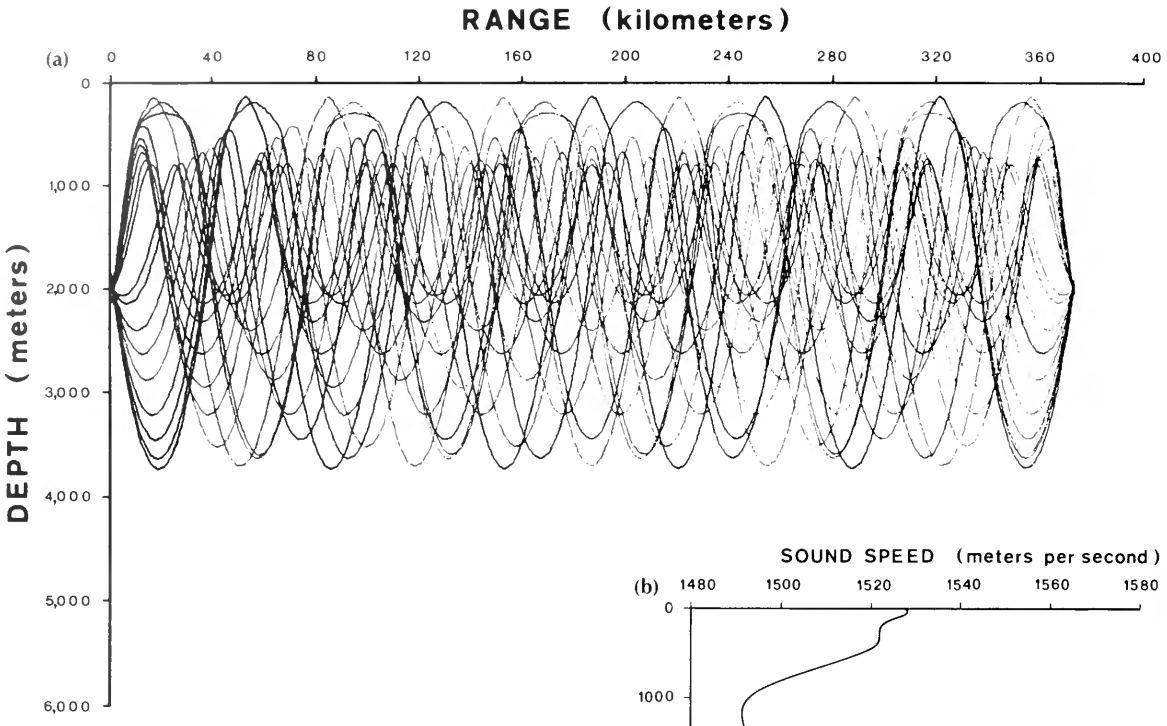
To understand ocean acoustic tomography it is important to know a little about how sound travels in the sea. The ocean is quite opaque to radio waves, but it is almost transparent to sound. In fact, sound waves of the right frequency (tones of certain pitch), emitted at certain depths, when transmitted can be received many thousands of miles away. Sounds from depth charges fired by the reseach vessel *Vema* off Australia in 1960 were received near Bermuda, a distance of 19,000 kilometers, or halfway around the world. It took the sound waves about 3.5 hours to traverse this distance because sound travels through water at about 1.5 kilometers per second, about three times faster than in air. An explosion is rich in many tones, but the low-frequency ones, say those below about 440 Hertz (the A440 that an orchestra tunes to), are the ones that easily travel the distance. Higher-frequency tones are rapidly diminished in intensity due to the absorption properties of seawater.

Sound is trapped in a duct-like channel formed by the characteristic change of sound speed as a function of ocean depth. Due to solar heating at the surface, the water there is rather warmer than at depth, and sound travels through it quickly. As depth increases, one encounters cooler waters with slower sound speeds. However, the density of the water increases with depth because of ever-increasing pressures, and this density change causes an increase in sound speed. Thus we have opposing mechanisms governing the speed of sound as a function of depth—decreasing speed because of cooler water and increasing speed as the result of increasing pressure. The overall effect is seen in Figure 3. There is a certain depth, called the axis of the SOFAR channel, at which sound speed is at a minimum value. SOFAR is an acronym for SOund Fixing And Ranging that derives from a plan used during World War II to triangulate the position of downed aircraft. Sound emitted at depths near the channel axis is alternately refracted upwards and downwards as it propagates, not striking either the ocean surface or bottom. It turns out that sound striking these boundaries usually is weakened greatly and does not contribute materially to what is received at long range.

A consequence of channeled propagation is that sound emitted by a transmitter travels to a receiver along many different paths. In a typical experiment, there can be as many as 15 to 20 distinct paths that connect the source to the receiver. Each path traverses a different portion of the ocean along its journey. Some paths stay close to the axis of the sound channel; they are therefore affected only by water features at this depth. Other paths cycle high up into the water column, grazing the surface, or deep beneath the axis, near the bottom. These paths are affected by a wider variety of water features.

Consider what happens to a pulse of sound such as that created by the explosion of the depth charge fired by the *Vema*. The pulse travels along many paths as it propagates away from the point of

A collapsed balloon at the top of a subsurface float. These are set to stay collapsed underwater, but when the float is released by acoustic signal and allowed to rise to the surface, the drop in pressure causes the balloon to expand, facilitating spotting from the surface vessel. (Photo by author)



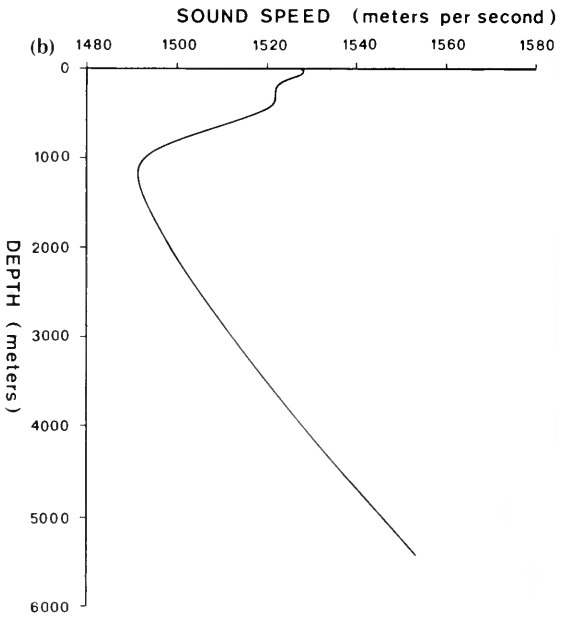


Figure 3. Refracted acoustic paths connecting a transmitter and receiver 370 kilometers apart (a) and a typical Atlantic Ocean sound-speed profile (b). Note the sound speed minimum at a depth of about 1,000 meters.

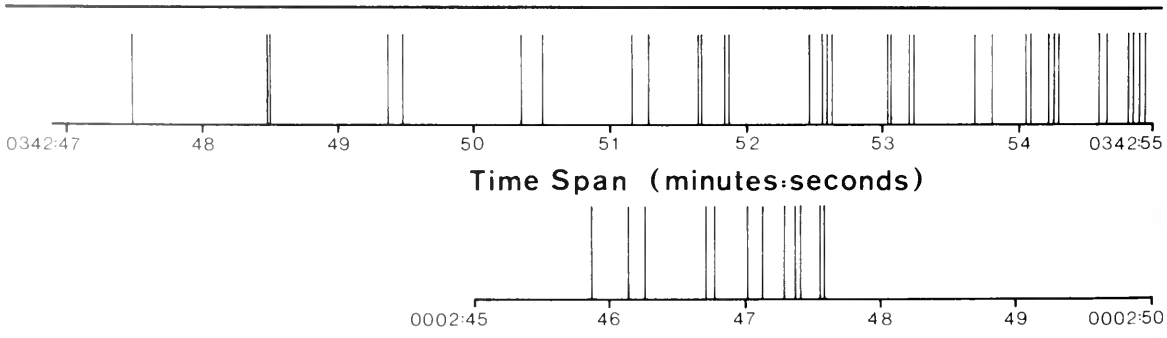


Figure 4. Pulse arrivals for the transmissions along the 19,000-kilometer Vema*-to-Bermuda paths (above) and along the paths of Figure 3a (below).*

firing. Those paths that strike the surface and bottom are reflected and weakened. Those that travel along wholly refracted paths are strong when they arrive at a distant receiver. They do not arrive all at once; rather they come in at slightly different times so the overall effect is to hear many replicas of the original explosion. The main reason for this odd behavior is that each path is slightly different in length; the time taken to travel each path is somewhat different. Furthermore, the mid-depth paths have slightly slower speeds than those cycling near the surface or bottom because the sound speed is slowest at mid-depths. Thus the pulses that travel along paths coming close to the surface and bottom arrive first, for they have traveled at faster speeds. Pulses traveling along paths near the SOFAR axis arrive last because they have traveled at the slowest speeds. Figure 4 shows the arrivals for the paths shown in Figure 3; it also gives an indication of how the sounds from the *Vema* explosion might have appeared as they arrived at Bermuda.

Enter Tomography

What we have described is the typical, steady-state, background, sound speed structure of the ocean and consequent acoustic propagation. Circulatory features slightly alter this backgound. Arctic or antarctic waters have unusually slow sound speeds associated with them because they are so cool. The Gulf Stream has warmer, and therefore faster, sound speed water. Mesoscale eddies can be warmer or cooler than surrounding waters, and therefore they speed up or slow down sound transmissions. Sargasso Sea water is very saline and has a faster sound speed than waters near the marginal ice zone, where freshwater glaciers and icebergs melt.

Not only do the properties of the water transported by a current affect acoustic travel times, but the currents themselves alter the speed of travel. If the sound is transmitted in a direction whereby the current aids its passage, the total travel time from transmitter to receiver will be shortened. Conversely, if the direction of transmission and the direction of current oppose one another, the transmission time will increase. In ocean acoustic tomography, these small speed changes allow researchers to detect differences in water masses and thus deduce circulatory patterns. They do this by measuring the variations in total travel time of sound pulses traveling between fixed sources and receivers. Figure 5 shows the effects of cold and warm water intrusion into a transmission path. A transmitter and receiver were deployed on moorings near a Gulf Stream meander. Between May 1 and May 9, the pulses arrived progressively later by about 0.6 seconds, whereupon they began to arrive earlier again. The influx of slow sound speed water during the first week of May, and the

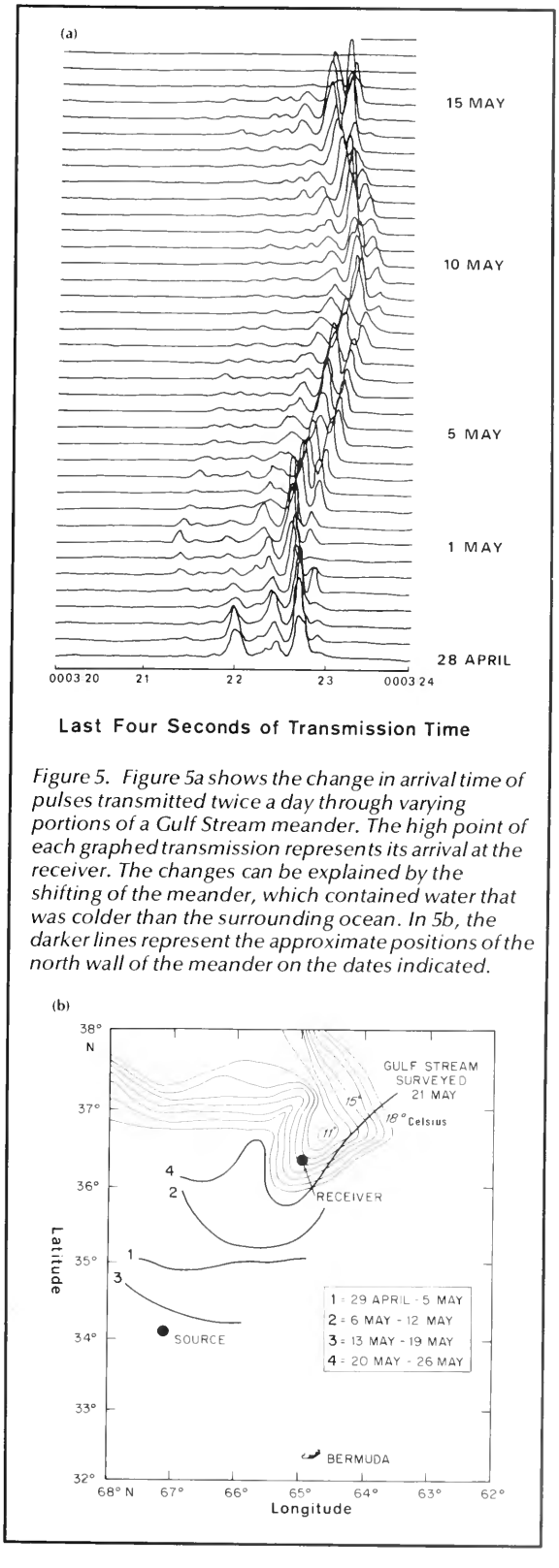
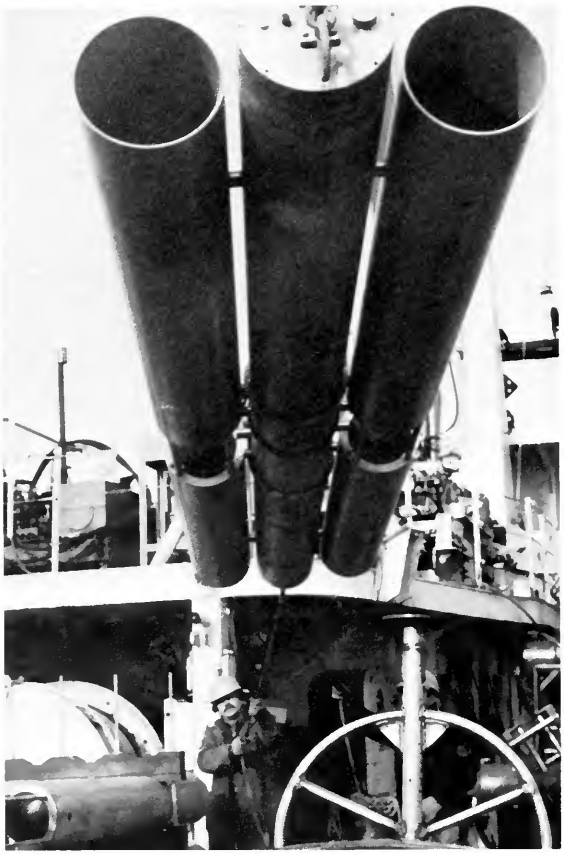


Figure 5. Figure 5a shows the change in arrival time of pulses transmitted twice a day through varying portions of a Gulf Stream meander. The high point of each graphed transmission represents its arrival at the receiver. The changes can be explained by the shifting of the meander, which contained water that was colder than the surrounding ocean. In 5b, the darker lines represent the approximate positions of the north wall of the meander on the dates indicated.



Acoustic transmitters used to generate underwater signals. The center tube contains a microcomputer and batteries. The outer tubes are like organ pipes — they generate the actual sound. (Photo by author)

movement of this water out of the transmission path beginning May 9, caused this behavior. Satellite imagery showed us that the north wall of the Gulf Stream wandered during this period. First it moved southerly, carrying cold water with it, and then it receded northward out of the path.

This experiment shows how it is possible to use the variation in travel time of acoustic signals to measure oceanic circulatory changes. An interesting earlier acoustic experiment, conducted during the early 1960s, yielded evidence of mesoscale activity. During a two-year period, precisely located and timed explosive charges were fired near the island of Antigua and were received near Eleuthera Island (in the Bahamas) and Bermuda. The object of the experiment was to determine the average travel time of signals through the ocean and thereby determine the average sound speed. Some results are shown in Figure 6. The arrival time of the pulses varied for several months by as much as half a second. This is consistent with what we now know about the ocean mesoscale.

These early experiments used only one or two transmitter-to-receiver paths and therefore yielded little detail about the intervening ocean. The imaginative leap taken by Munk and Wunsch employed multiple transmitters and receivers in a special way. Their system is based on exactly the same type of travel time measurement, but it provides much finer resolution of the interior ocean. It is easy to see why it is so appealing, compared with conventional methods. Only a few transmitters and receivers are needed for adequate sampling of large ocean expanses. Each of N transmitters sending pulses to each of M receivers

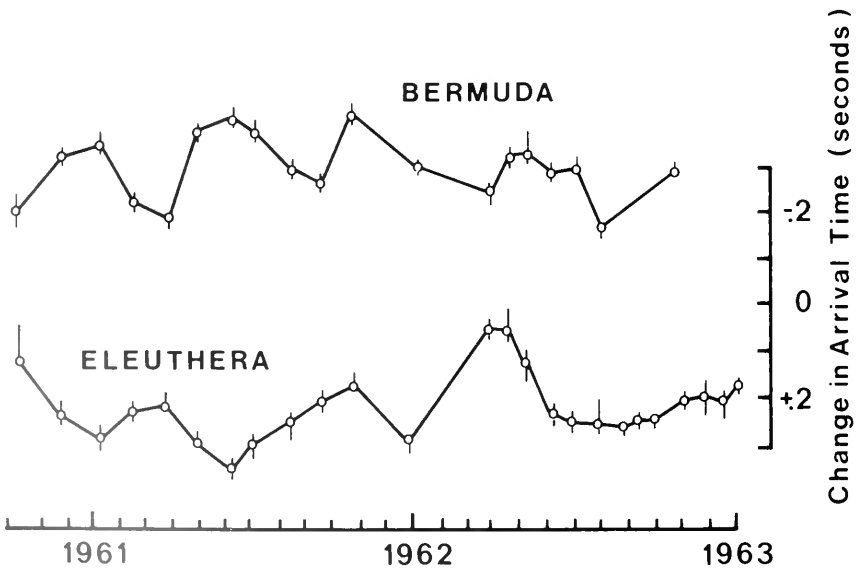


Figure 6. Changes in the travel time of sound waves from explosions detonated near the island of Antigua over a two-year period. The sound waves were received near Eleuthera Island (in the Bahamas) and Bermuda. (After G. Hamilton)

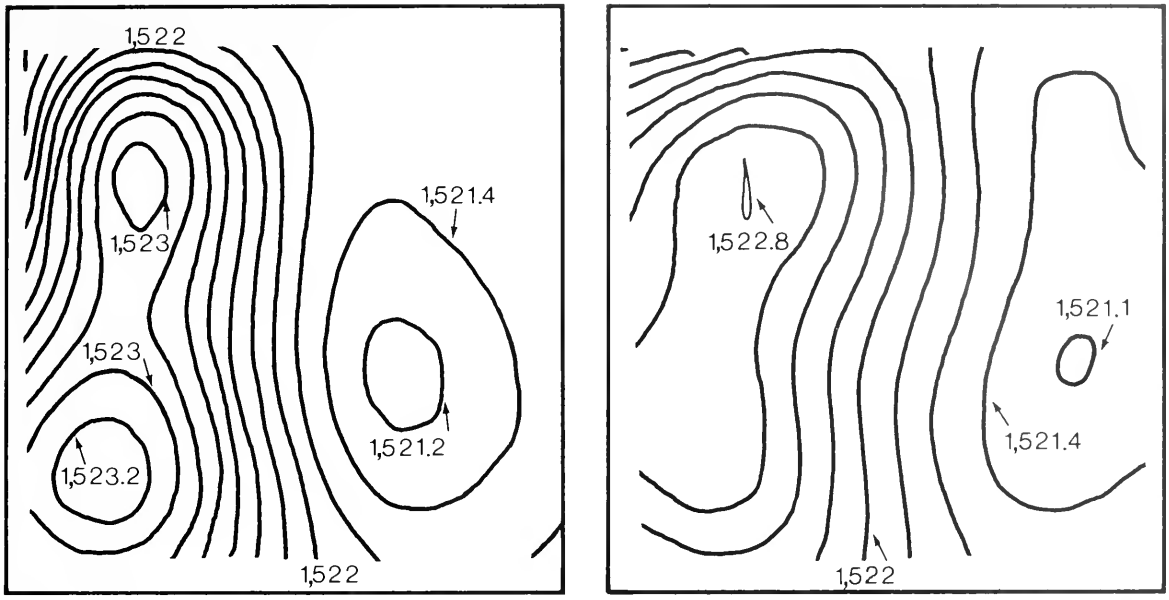


Figure 7. Sound speed contours in the Mid-Ocean Dynamics Experiment (MODE) area (300 kilometers square) at a depth of 500 meters, from traditional equipment on the left and simulated tomographic results on the right. Numbers refer to the speed of sound in meters-per-second along a particular contour line. (Drawing courtesy of B. Cornuelle)

results in N x M horizontal sampling paths. Moreover, each separate transmitter-receiver pair has many vertical paths, thereby sampling the entire water column as well. Conventional oceanographic measuring techniques—such as current meters; sound velocity meters; temperature, salinity, and depth probes; and water bottles—yield information only at a single point. They must be transported through the ocean by costly ships or aircraft. If a ship lowers a conventional suite of instruments on a 20-mile grid, it takes about three weeks to sample a 200-mile square of 5,000-meter-deep ocean. Even then, the resulting picture is not really synoptic. The image is smeared or blurred much the way a photograph blurs when the subject moves because, during the course of a survey, the ocean circulatory pattern changes. In contrast, acoustic tomography can give synoptic pictures in a matter of minutes.

A Computer Example

During the Mid-Ocean Dynamics Experiment (MODE) in the mid-1970s, a series of moorings with current meters and precision temperature and pressure meters was deployed in a roughly 500-kilometer square in the southern North Atlantic near 25 degrees North, 70 degrees West to learn about mid-ocean variability. Contours of measured sound speed at a depth of 500 meters are shown in Figure 7. Data were obtained from 16 moorings equipped with 83 current- and temperature-measuring instruments. Bruce Cornuelle, a Woods Hole Oceanographic Institution-Massachusetts Institute of Technology graduate student, used this information to conduct a computer simulation of an ocean acoustic tomography experiment to see how well tomographic techniques would work. His simulation used only four transmitters and four receivers. The favorable comparison between simulation and observation data provided one of the last bits of encouragement needed to embark on a real at-sea test of tomography.

An Ocean Demonstration

It seemed like serendipity that just as the idea of tomography in the ocean emerged, so did the technology to implement it. As is often the case in the *pas de deux* of science and technology, the dancers alternate leads. Perhaps it was the development of low-frequency pulsed transmitters (variants of the Webb neutrally buoyant SOFAR floats used to track subsurface currents), or the development of computer-controlled acoustic receivers that triggered the idea of tomography. Perhaps the idea came from elsewhere, from medicine or earth science. In any event, the technology to design a test experiment emerged almost simultaneously with the idea itself.

In the early part of 1981, four transmitters and five receivers were deployed in the MODE region. They were attached at a depth of about 2,000 meters to specially designed, taut, subsurface moorings (Figure 8). Tension and the lack of surface wave activity helped ensure that the moorings did not move about excessively in the internal tidal currents. Any motion of the instruments would

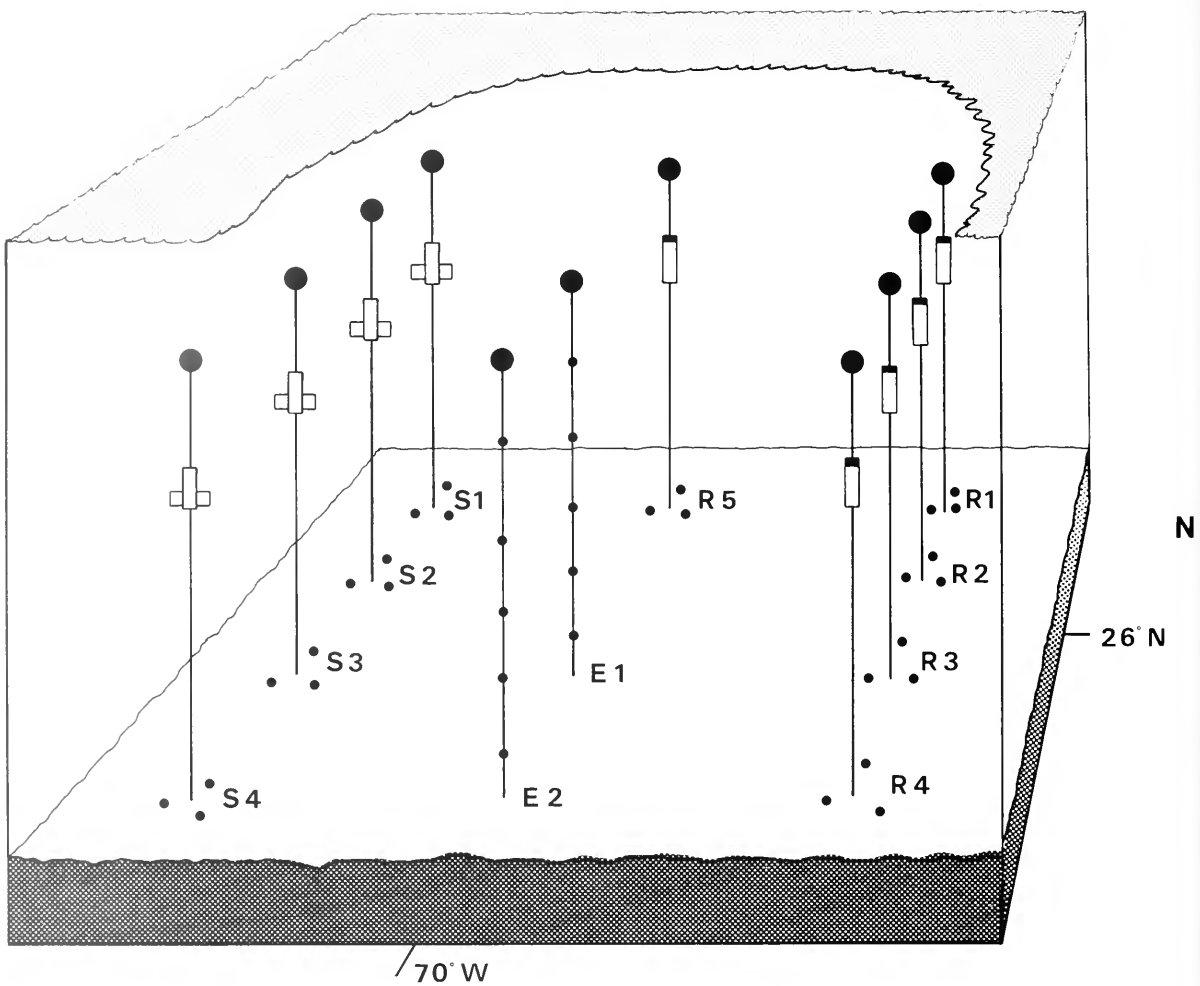


Figure 8. This configuration of the 1981 experiment shows moorings with transmitters (S1 to S4) and with receivers (R1 to R5). Moorings E1 and E2 measured currents and temperature by conventional methods to help establish a "ground truth," or basis for the comparison of data. The three dots at the base of most moorings represent acoustic transponders used to trace the motion of the moorings.

shorten or lengthen the total acoustic transmission path; this could result in a change in travel time that might be misinterpreted. To further guard against this error, each mooring was equipped with a small acoustic navigation system to record mooring motions. Each also was provided with a precision atomic clock, so that changes in travel time could be measured as precisely as possible. Pulses were transmitted between all instruments on a continuous basis for six months. Periodically, a ship was dispatched to the area to conduct a conventional oceanographic survey, using a suite of instruments lowered on a wire (measuring temperature, pressure, conductivity, and sound velocity). These surveys would serve as the basis against which the tomography data would be measured.

What happened? How did the new idea and technology work? Some results of the experiment are shown in Figure 9. This figure shows the sound contours of the area at a depth of 700 meters. The two outer panels are the data from ship surveys using conventional instruments, while the center panel is a result of the acoustic tomographic system for a day between the two conventional surveys.

The first survey shows a strong, cold eddy centered in the experiment area. It is characterized by abnormally slow sound speed. The later survey shows that this eddy moved off to the west, and a new, smaller eddy formed in the southeast. In addition, a front developed, running approximately northwest to southeast. The tomographic diagram depicts the situation midway between the two surveys. The major cold eddy is seen moving off to

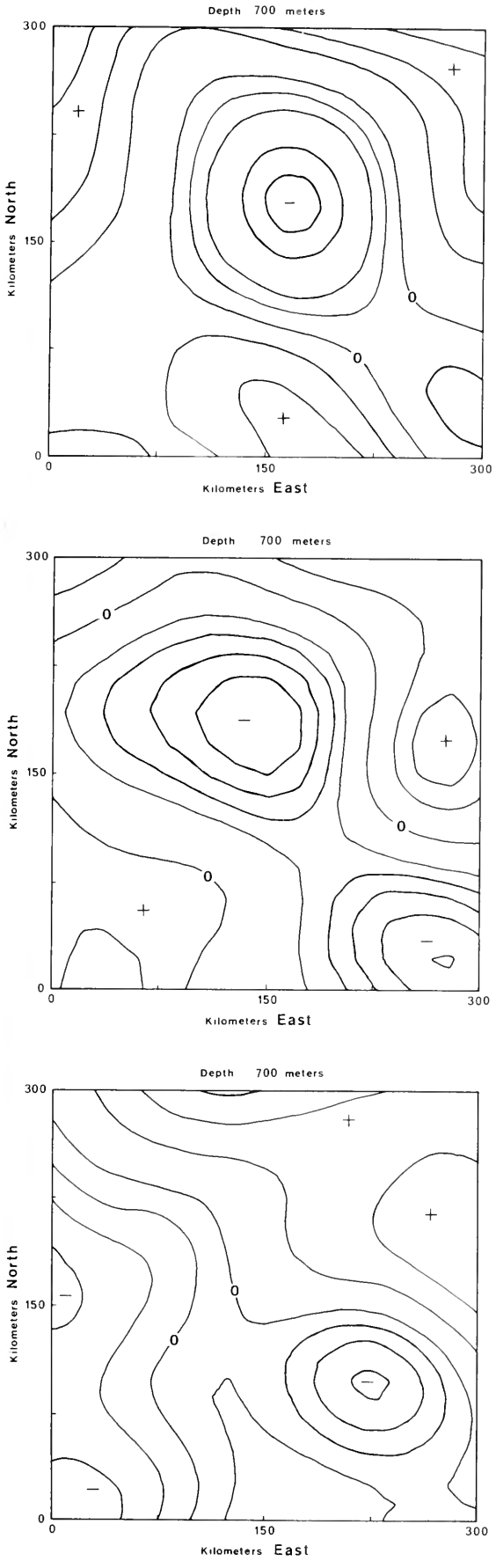


Figure 9. Some results of the 1981 experiment. The top and bottom panels are the results of ship surveys, while the center panel is the tomographic version. The lines, contours of constant sound speed at a depth of 700 meters, are relative to a reference speed; negative contours signify low sound speed in cold water. The cold eddy in the center of the surveyed area (top panel) began spreading and moving to the northwest (center panel) and is almost out of view in the bottom panel. The new eddy forming in the southeast (top panel) moves progressively to the northwest. A frontal system, separating cold and warm water, advances from the northeast.

the west, the frontal system is developing, and a new cold eddy is beginning to move in from the southeast. A synoptic picture, a "snapshot" of the ocean, has been produced.

The Next Steps

These results are the first available from the experiment. They are extremely encouraging because they appear to reflect quite accurately the major mesoscale features in the experiment area. A more thorough and rigorous analysis of the tomographic data will undoubtedly result in more detailed maps. A sequence of maps can be produced rather simply to show the evolution of the ocean on a daily (or even hourly) basis. The major objective of the experiment, to test the feasibility of ocean acoustic tomography, was accomplished.

There are many important aspects of the ocean that are still hidden to us but that may be revealed by tomographic measuring techniques. The complicated structure of the meandering Gulf Stream can be observed without actually having to put instruments inside the swiftly flowing current. Large ocean basins can be observed in an economical, timely fashion. It is possible to combine many other information resources, such as satellite images or altimeters, with ocean acoustic tomography to provide more reliable predictions and forecasts of oceanic events and their impact on climate and weather. This initial foray is just the beginning.

Robert C. Spindel is an Associate Scientist in the Ocean Engineering Department at the Woods Hole Oceanographic Institution. He was recently recipient of the British A. B. Wood Medal for distinguished work in acoustics.

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Ocean Hot Springs:
A Status Report

by John M. Edmond

The most exciting development in oceanography in recent years has been the discovery and systematic sampling of deep-ocean hot springs at various locations in the Pacific Ocean. Unusual life forms and geological structures have been found at vent sites 2,000 to 3,000 meters deep, the first of which were detected off the Galápagos Islands in 1976. Other vent discoveries followed, off Mexico, just recently off the coast of Washington and Oregon, and in the northwestern Pacific.

This article will bring the reader up to date on this research, which involves all branches of oceanography — biology, chemistry, geology and geophysics, physical oceanography, and ocean engineering. In fact, the oceanographer's conception of the ocean is rapidly changing as a result of these investigations.

The three pioneers of this research are Robert Ballard, a geologist at the Woods Hole Oceanographic Institution, Jean Francheteau, a geophysicist at the University of Paris, and Peter Lonsdale, a geologist at Scripps Institution of Oceanography in California. These men have dived to the vent sites in the submersibles *Alvin* and *Cyana*. Other scientists wanting to explore the vents have relied on their expertise in selecting suitable diving sites. First an accurate topographic map of the survey site is needed. This is made by using the Seabeam multibeam sonar array, a commercial version of a highly sophisticated system developed by the U.S. Navy. Accurate charts of the rough underwater terrain are produced that are comparable to those used on land. A photographic survey of the underwater terrain is then made using *Angus* (Acoustically navigated geophysical underwater system), an unmanned, sled-like vehicle that carries cameras and is towed ("flown") above the bottom terrain. After that operation a submersible is deployed to explore vent sites of interest.

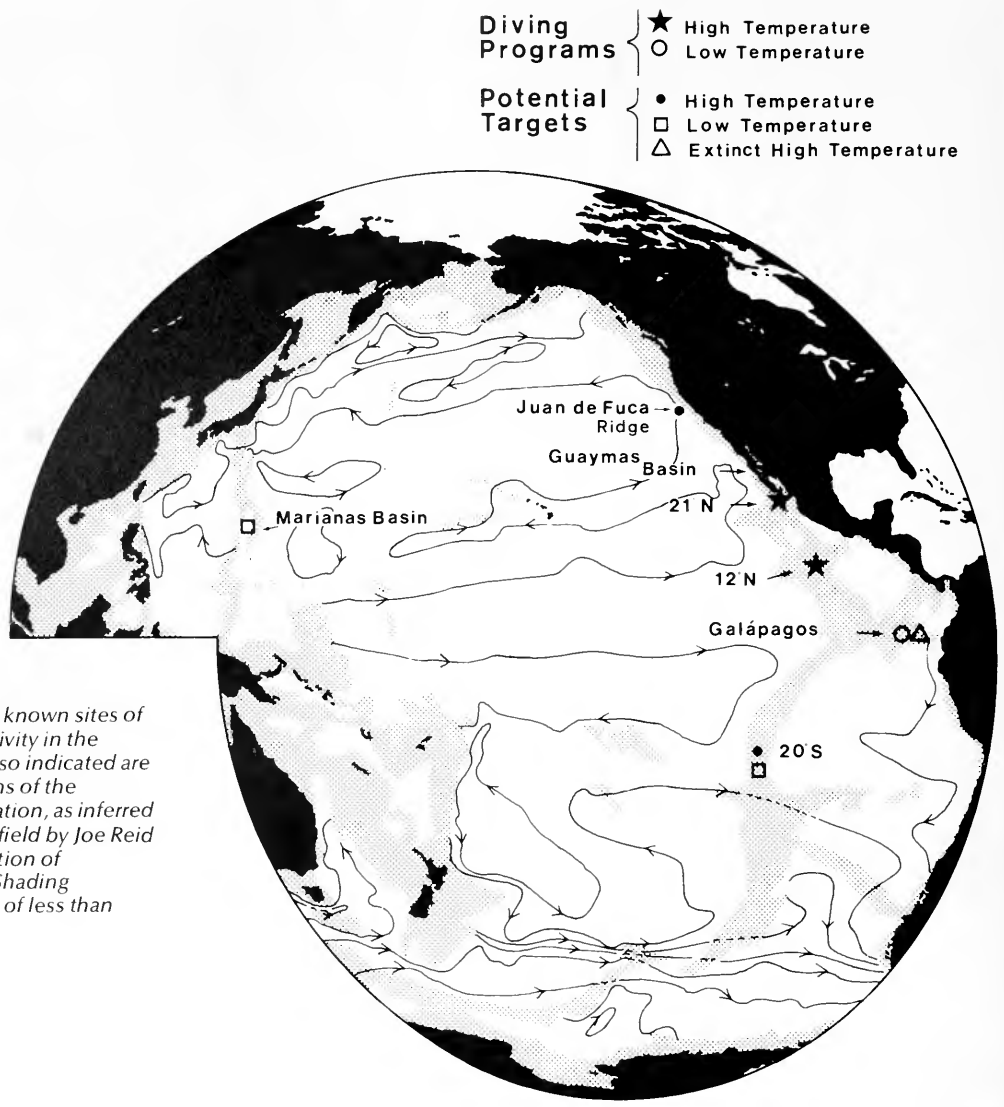
In the initial discovery of hot spring fields — at the Galápagos spreading center (see *Oceanus*, Vol. 20, No. 3, 1977) — scientists found them to be "oases" of organisms, most of them conveniently large and white. The active springs were even surrounded by a "halo" of cream-colored Galatheid crabs. The high visibility of these organisms aided scientists in the search for hydrothermal activity.

During the last five years, the exploration program has progressed. We now know where these hot springs are likely to be — along plate boundaries where the earth, as in the case of the East Pacific Rise at 21 degrees North, is separating at a rate of 6 centimeters a year, creating new seafloor through volcanic activity. Shortly after the Galápagos discovery of vents with relatively low water temperatures (20 degrees Celsius above ambient), Francheteau stumbled on extinct "chimneys" on the crest of the Rise, containing sulfide ore deposits of zinc, iron, and copper (see *Oceanus*, Vol. 23, No. 2, 1980).

From the chemical studies of seawater at the Galápagos springs, we had concluded that temperatures must reach about 350 degrees Celsius somewhere in the system, to allow for the compounds found. Impressed as we were by the highly permeable nature of the oceanic crust, as observed from *Alvin*, we did not think that mineral-rich solutions could reach the seafloor undiluted by cold water. Francheteau's discovery demonstrated, however, that this did indeed happen.

In 1979, Ballard and Francheteau, in a followup expedition to 21 degrees North, dove in *Alvin* and found "black smokers" — chimney-like structures pouring out 350-degree solutions containing iron, copper, and zinc. On hastily arranged dives later in the same year, the author and other scientists managed to carry out some preliminary samplings of these systems. Chemistry tests affirmed the high-temperature range we had anticipated from the Galápagos. In addition, the metal concentrations in these spring waters marked

Black smokers at 21 degrees North on the East Pacific Rise, photographed from Alvin. *The 350-degree waters exist as clear, homogeneous solutions but turn "smoky" when they mix with the cold, alkaline water column. This mixing also causes very fine particles of iron, copper, and zinc sulphides to precipitate. Crawling down the chimney at left is a crab of the Brachyura family. In the foreground are water samplers mounted on* Alvin. *(WHOI photo)*



Map of the major known sites of hydrothermal activity in the Pacific Ocean. Also indicated are the flow directions of the mid-depth circulation, as inferred from the density field by Joe Reid of Scripps Institution of Oceanography. Shading represents depth of less than 3,500 meters.

them as the type of ore-forming solutions responsible for generating the massive sulfide deposits that are exploited on land as major sources of base metals. Dives in November of 1981 enabled us to sample both the smokers and the lower-temperature vents in detail.

The discovery of the black smokers stimulated a major expansion in the exploration campaign. The joint United States–France program has subsequently identified numerous areas of hydrothermal activity on the East Pacific Rise. This work culminated recently in a series of dives by *Cyana* at 12 degrees North, where smokers were found in almost continuous activity along 18 kilometers of the ridge crest. In all cases, exit temperatures were within a few degrees of 350 degrees Celsius. Chimneys and associated ore deposits were abundant.

In parallel with this work, other investigators have helped extend our knowledge of the distribution of the hot springs. Alex Malahoff, chief scientist for the National Ocean Survey, a branch of the National Oceanic and Atmospheric Administration (NOAA), has found a huge extinct sulphide deposit on the same ridge segment as the original Galápagos discovery. If on land, this ore body would certainly be exploited. Scientists from the U.S. Geological Survey have found evidence of active sulphide deposition on a large scale on the Juan de Fuca Ridge, within 500 kilometers of the Oregon coast.

Perhaps the most exciting discovery, however, was in a different geological environment — the Gulf of California, also known as the Sea of

Cortez. Here the East Pacific Rise is actively rifting the Baja Peninsula away from the mainland. The spreading center has been buried by river sediments. Rather than the lava lakes and pillow basalts typical of the open ocean, here the eruptions take the form of lava injections into the sediment pile as dykes and sills. Since the sediments are relatively coarse-grained, hydrothermal convection occurs within them. Very high heat flow has been reported from the area, and Peter Lonsdale found large "mounds" over the spreading axis by using the side-scan sonar system on Deep Tow, Scripps' towed vehicle. He also recovered massive samples of sulphide which, amazingly enough, were saturated with oil! The plastic liner of a piston core melted at a depth of 10 meters into the sediment. Deep Sea Drilling Project holes over the axis turned up abundant evidence of active hydrothermal activity, penetrating through hot basaltic sills.

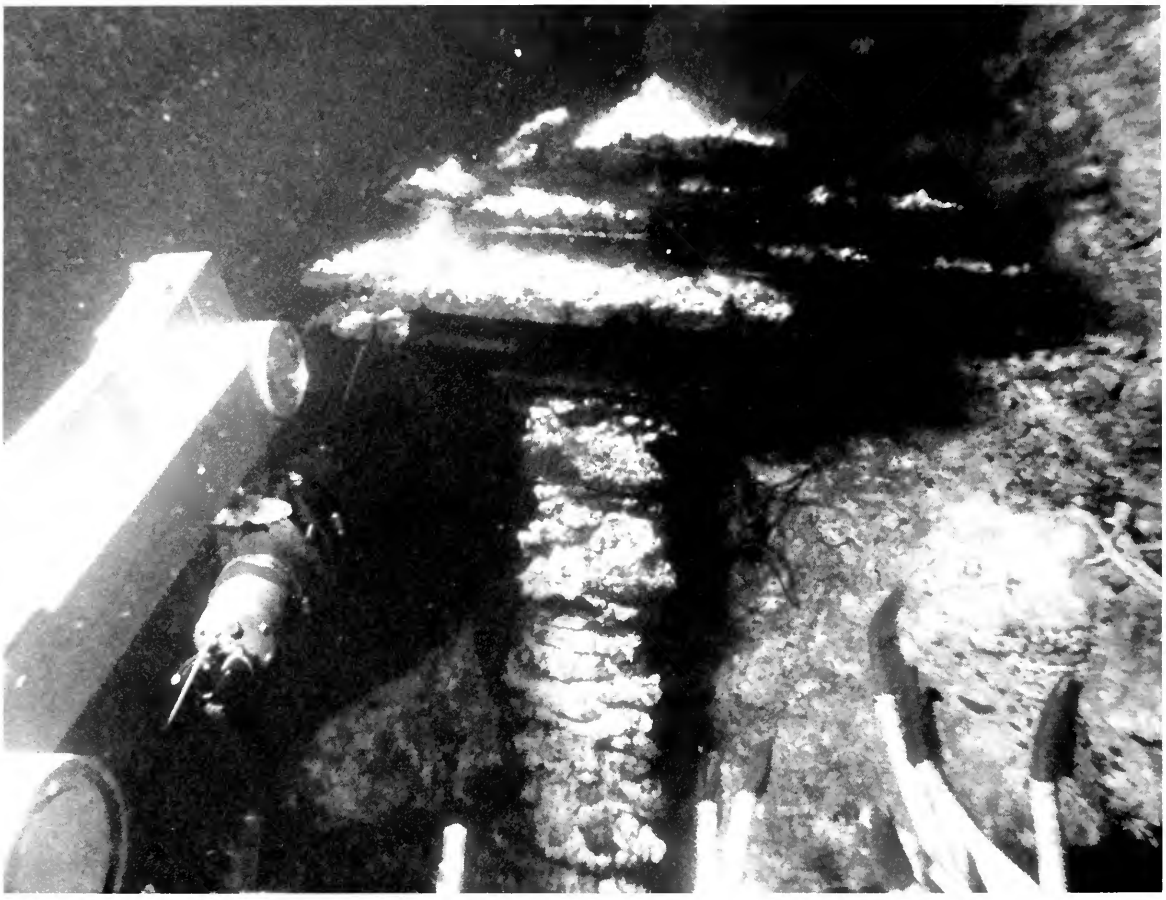
Lonsdale organized a cruise to the Gulf's Guaymas Basin in January of this year, with spectacular results. The mounds, hundreds of meters long and several tens of meters tall, are surmounted by huge edifices, shaped rather like Japanese pagodas, venting water at temperatures of up to 315 degrees Celsius. The "temples," photographed by the crew of *Alvin*, are covered with dense groves of tube worms that seemingly live uncomfortably close to the hot vent waters. Mats of giant bacteria, unlike anything viewed previously, cover the surface of the surrounding sediments, and in some cases appear to be in the process of smothering the worms. There are groves of black coral, looking for all the world like hedgerows in winter, large red crabs, and big white octopuses. In the venting waters, oil occurs in an immiscible phase. There are crystals of wax in the sulphide chimneys, and tar is everywhere. The Gulf is an area of very high biological activity; we saw spectacular displays of bioluminescence. Some of the abundant planktonic carbon is incorporated in the sediments. Today, high temperatures are "cracking up" the organic molecules to form the hydrocarbons that are swept out by the hydrothermal circulation. Apparently the food chain around these hot springs can exploit these hydrocarbons. Certainly the abundance and diversity of life in the Guaymas Basin are much greater than anywhere yet observed on the bare basalts.

The French submersible Cyana, *being launched from its mother ship, the* Noroit. *(Photo courtesy of Centre National pour l'Exploitation des Oceans)*

The first ridge-crest hot springs discovered were the Red Sea brines. The flanks of the Red Sea are underlined with evaporites, sea salt that precipitated when the Red Sea dried up during the Miocene Epoch. The brines, though hot, are heavy enough, because of the very high concentrations of dissolved salt, to pond on the bottom. Their extremely slow dissipation allows the precipitation of the heavy metals brought in by the springs below, forming a very rich ore deposit. In the Gulf of California, the sediment itself acts as a trap. The whole sediment column is mineralized to produce a large ore deposit of the Besshi type, named after a well known example mined in Japan.

Other work by Lonsdale in collaboration with Roger Anderson of Lamont-Doherty Geological Observatory and scientists of the University of Tokyo suggested that a similar situation occurs on the Marianas Spreading Center, an area between the Marianas Arc and the South Honshu Ridge, in the western Pacific. In this case, the axis is buried by sediments derived from volcanoes. By tracing the flow of methane plumes in March of this year, a joint Scripps–University of Tokyo research expedition

"Young" petroleum oozing from a Guaymas Basin rock. (Photo by Fred Grassle, WHOI)



A temperature probe on Alvin*'s arm measures the heat of water venting from a pagoda-like mineral deposit in the Guaymas Basin. The tube worms (Riftia pachyptila) in the foreground are blood red and protrude from white plastic-like tubes. They grow to nearly 2 meters in length. (Photo by Robert Brown, WHOI)*

found evidence of the first known off-ridge vents, in the Mariana Trough, to the east of the spreading center. Yoshio Horibe of the University of Tokyo led the expedition.

Attention also is beginning to focus on slow-spreading ridges, such as those in the Mid-Atlantic. All the discoveries to date have been on axes with total spreading rates of at least 6 centimeters per year. The Mid-Atlantic Ridge spreads less than 2 centimeters per year. A number of years ago Bruce Heezen of Lamont-Doherty reported seeing large clams on the crest of the Reykjanes Ridge during a dive of the nuclear-powered Navy research submarine *NR-1*. At that time, the association between clams and hot springs had not been made. Peter Rona of NOAA had established that there appeared to be hydrothermal activity on the Mid-Atlantic Ridge itself at 27 degrees North. Although this location is the "pole of inaccessibility" for the north Atlantic, 1,200 nautical miles from any port, the weather is favorable for diving. We plan to explore this area in a joint NOAA-WHOI expedition this summer.

With the initial flood of discoveries now being digested, it is time to take stock and project the next moves. The evidence gathered to date suggests that the chemistry of the hot springs on the open ridges is quite uniform. This is not surprising, given the compositional uniformity of the two reactants, tholeiite basalt and seawater. On buried ridges, of course, the situation is drastically different depending on the chemistry of the sediments, since they also participate in the hydrothermal reactions. What is needed now is a detailed understanding of the chemical processes themselves.

In the simplest case, one would expect the dissolved concentration of a mineral to be determined by an equilibrium with its solid phase. We know this is the case for dissolved silica, the solid being quartz. However, the thermodynamic data available at present is inadequate to explain the

situation for other possible solution-mineral pairs. Since we do know the range of possible solutions, future experimental work can be focused exactly upon this particular problem. Kinetics must be crucial. In the open or flowing systems of convecting fluids, the determining role is played by reaction rates, rather than equilibria. This is a more complex area of experimental study, since the reaction regime, flow rates, temperature, pressure, and other factors all must be specified. To do this will require much more information on the geology and hydrology of these systems.

One can see directly into oceanic crust only in ophiolites, the great slabs of seafloor that were thrust up onto the continents during collision processes. Although studies of these slabs indicate that seawater can penetrate to depths greater than 5 kilometers, even into the mantle, the investigations to date have been insufficiently detailed to provide the parameters needed for thorough kinetic studies. The recent success of the Deep Sea Drilling Project in drilling deep holes into the oceanic crust may help in this regard. However, the holes can be drilled only in relatively old crust, outside the zone of high-temperature reaction. Thus the cores obtained will be most valuable in giving the total interactive history of the basalt with seawater, a history that spans both a high- and a low-temperature phase.

Extension of the exploration program to other ridge systems is already under way, limited only by resources and logistics. Fracture zones are presently off limits due to their depths. Earthquake data show appreciable activity in fracture zones to depths in excess of 10 kilometers beneath the seafloor. Brittle fracturing occurs only at temperatures below 500 degrees Celsius, suggesting that water may penetrate to great depths. These very deep-seated hot springs will be exciting objects of study once very deep-diving submersibles become available.

Hydrothermal activity at spreading centers appears to exert a major influence on the chemistry of seawater. However, there are considerable uncertainties as to the exact magnitudes of the chemical fluxes involved, uncertainties that will not be appreciably reduced by accumulating more compositional data from newly discovered systems. We will never be able to sample more than a tiny fraction of the presently active areas. Flux estimates from a given system will not be more than guesses in the foreseeable future. An integral measure is needed. A start on this could come from the investigation of water-column anomalies in the flowlines of deep waters that have passed significant segments of the axis: in the central South Pacific, for example, where the gyral circulation at mid-depth has an eastern limb that flows along the crest of the East Pacific Rise for at least 1,000 kilometers before turning west across the ocean. A well-developed helium plume delineates this flow. In principle, the chemistry of this water mass can tell us the whole story of additions and removals in the hydrothermal circulation along this major segment of the rise. However, a major effort in analytical chemistry will be required before this situation can be fully exploited for science.

These two fish were trapped in the hatch area of Alvin *at the East Pacific Rise in November of 1981. Now called the "21 degrees North vent fish," their genus and species are yet to be identified. They are members of the family Zoarcidae. (Photo by Jean-Louis Michel, CNEXO)*

In less than five years, research has established ridge-crest hydrothermal activity as an integral part of the sea-floor spreading process. Every exploration cruise mounted in the last four years has been successful. The science of oceanography has been transformed. Two major types of ore deposits have been seen in the process of formation, with obvious implications for exploration and exploitation on land. The seas still have their secrets!

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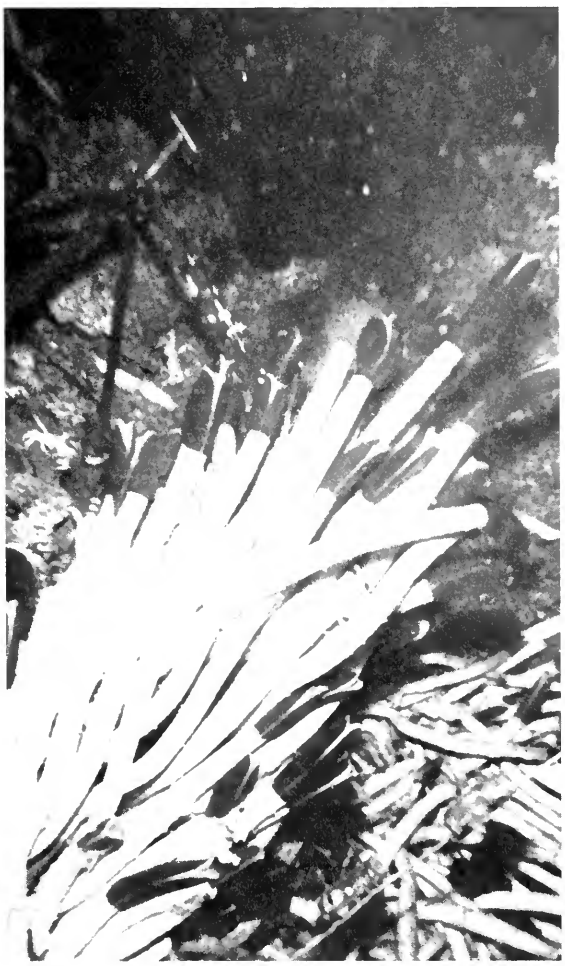
Galatheid crab

Hot Vent Life Forms

Some 40 marine scientists from 20 universities and research institutions participated in the recent "Oasis" expedition to the sites of hydrothermal vents off Baja California, Mexico. The five-week journey, in April and May of this year, allowed scientists from the United States, Mexico, and France to explore the vents with the submersible *Alvin*, operated by the Woods Hole Oceanographic Institution. The photographs on these two pages were among the many pictures taken on the expedition, which was funded by the National Science Foundation and coordinated by Scripps Institution of Oceanography.

Located nearly 240 kilometers south of the Baja peninsula, 21 degrees north of the equator, these hot water vents are at depths of about 2,550 meters along the East Pacific Rise. The Rise is a volcanic ridge along the top of a spreading center, on the boundary of two of the earth's jigsaw-puzzle-like plates. The vent water reaches temperatures in excess of 350 degrees Celsius, whereas nearby seawater is only 2 degrees.

Life is sparse over most of the ocean floor, but dense communities of life surround the vents, thriving without the aid of sunlight in waters abundant in bacteria and other microorganisms.

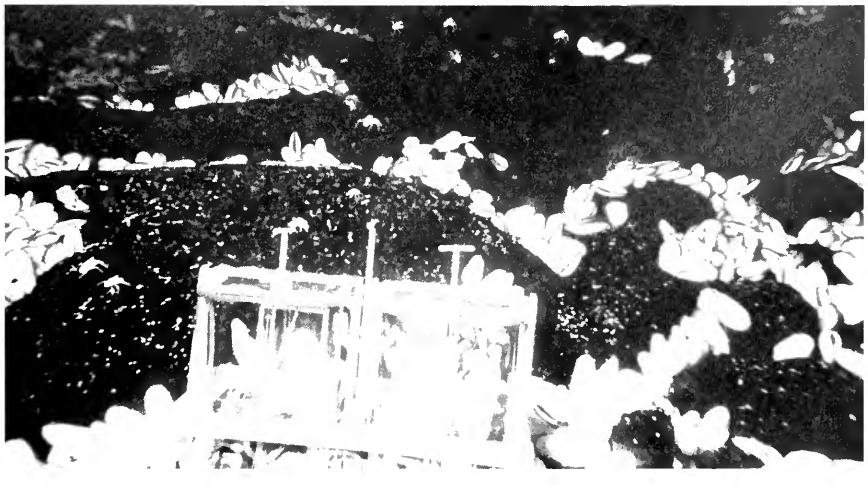


A cluster of tube worms (family Vestimentifera), along with crabs and sampling equipment. (Photo by Horst Felbeck, Scripps)

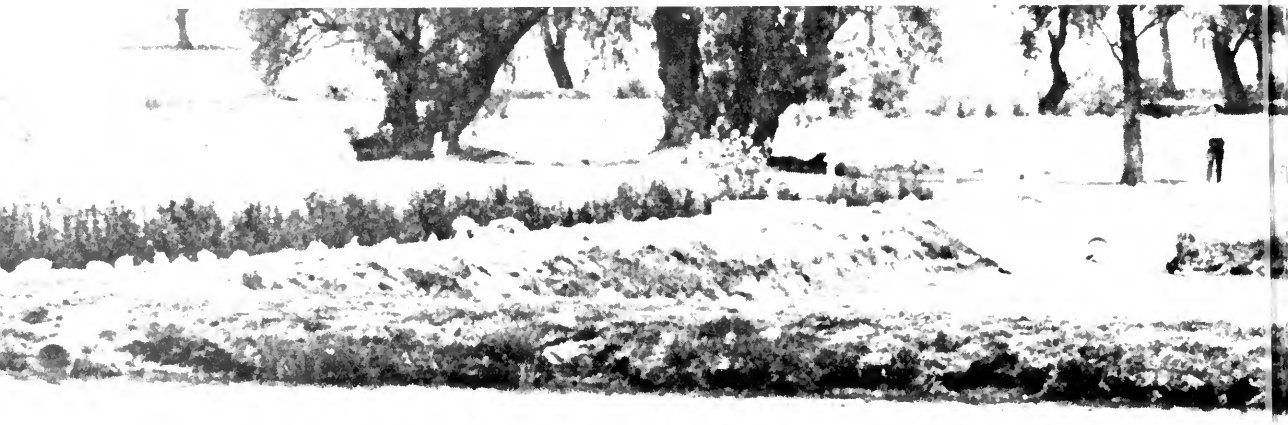
Oxidized metallic sulfides on the seafloor. The broken pieces appear to be remnants of extinct chimneys. (Photo by Fred Grassle, WHOI)

and Sea-floor Geology

This busy scene shows a crab of the family Brachyura entering a trap. To the left of the trap is a weight that has been jettisoned by Alvin *to adjust buoyancy, and at the far left is a basket containing clams that have been collected by* Alvin*'s pincer arm. Part of* Alvin*'s arm can be seen at upper right, and below it is a "slurp gun," used to vacuum up small organisms for study. The white dots on the basalt seafloor are a new species of snail discovered on this expedition. (Photo by Roberta Baldwin, Scripps)*

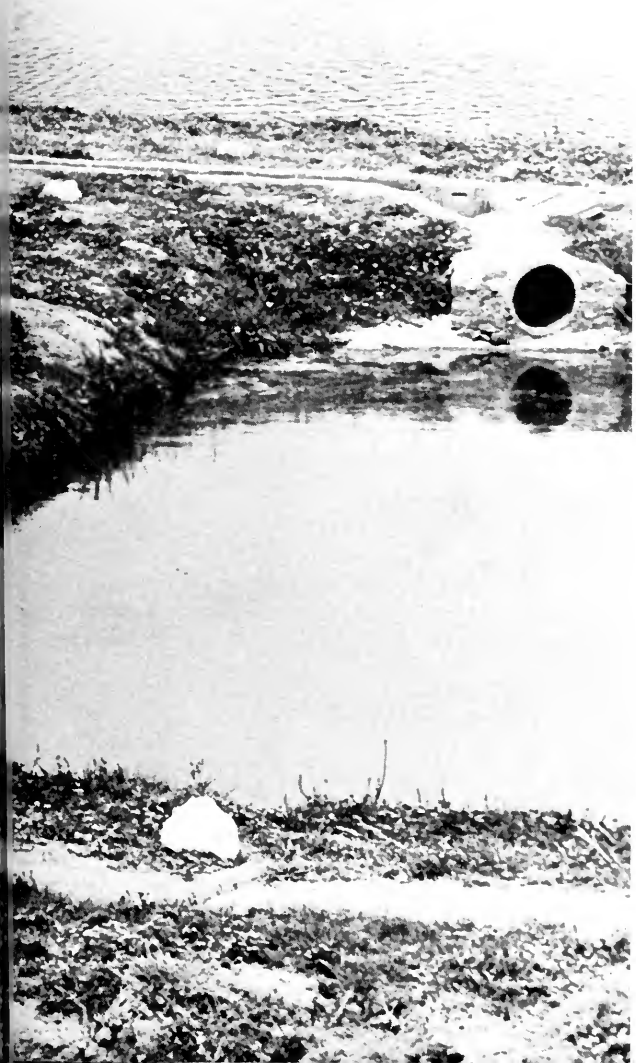


At this clam field, scientists have used Alvin*'s manipulator arm to place some clams in a respiration chamber, which measures the animals' respiration in their natural environment. (Photo by Carl Wirsen, WHOI)*



Pitfalls in Third World Aquaculture Development

by Leah J. Smith
and Susan Peterson



Aquaculture — raising marine or freshwater animals and plants in controlled environments — has been suggested as a partial solution to world food problems. Development projects in the Third World have been supported by international, national, and private agencies interested in improving the quality and quantity of food throughout the world. Some of these projects have failed: some because of inadequate attention to social, economic, and political factors; others because of inadequate understanding of the mechanics of fish culture. Learning from these mistakes, developers of Third World aquaculture can plan future projects more carefully.

Variations and Constraints

There are as many variations in techniques for fish farming as there are for growing other crops. Each fish farmer must decide on a crop appropriate to his region, land, and market, and then prepare the pond, procure seed, introduce fish, add nutrients, harvest, process, and sell or distribute the crop. Fish farmers are constrained by seasonal changes, weather, disease, predation, and the lack of materials, capital, parts for machines, trained labor, or management experience. They also may be affected by other local food-producing sectors, such as agriculture and capture fisheries. Furthermore, local, regional, or national governments may be responsible for constraints in the form of laws, lack of educational or training

Freshwater fish farm at Chapingo, Mexico. (Photo courtesy of FAO)

Placing spawning beds in ponds (left) at a fish farm in Chapingo, near Mexico City. This project is run by the Mexican government. Carp in these ponds can be harvested with nets (right). (Photos courtesy of FAO)

facilities, inefficient capital flow, poor transportation facilities, or inadequate marketing systems.

An individual, family, cooperative, or large business may operate a fish farm, using an artificial environment (a newly dug pond, an irrigation system adapted to aquaculture, a concrete tank) or a natural one (an existing pond, bay, or protected waterway). A freshwater system may require adapting land use from agriculture or irrigation. In the Far East, fish of the genus Tilapia are grown in rice fields, where the fish and the rice are harvested simultaneously. An attempt to transplant this practice to Egypt failed, however, primarily because the rice-growing season there is shorter. When the Egyptian rice fields were drained for harvesting, the Tilapia had only just reached their breeding period.

Brackish and saltwater aquaculture will not necessarily disrupt or displace traditional agriculture but may affect traditional fishing, seaweed harvesting, or other uses of bays, estuaries, mangrove swamps, or shallow-water areas. Floating cages, raft systems, elaborate net enclosures, and other structures may be used to keep fish or shellfish within the control of the farmer but may demand accommodation by other users of the area, who may be accustomed to unregulated harvesting or unrestricted passage.

Regardless of the physical setting, aquaculture production requires a source of broodstock or seed, nutrients, good water quality, and the means of controlling predators and disease. In addition to raw materials, engineering and biological knowledge are necessary to design and operate the system.

Cultured fish are harvested in several ways. In artificial enclosures or ponds, fish are "herded" to one end of an enclosure and then netted, or the ponds are drained. In open systems, fish or shellfish may be grown in racks, from rafts, or in cages that can be pulled or harvested periodically. Aquaculture harvesting techniques have definite marketing advantages over capture fishing. For example, draining a pond produces predictable quantities of fish at one time, and periodic harvesting allows for appropriate timing of deliveries to the market and distribution of income or protein on a regular basis.

Aquaculture products can be prepared in several ways. If fish are destined for sale near the production site, they can be sold fresh whole or may be gutted, gilled, or headed before being chilled and sent to market. In areas where the growing site is some distance from market, fish may be chilled on ice, frozen, salted, smoked, or dried. The processing technique need not be elaborate; in many places such processing is done by women, old men, or adolescent children, with minimal capital equipment. For new products, special marketing studies or promotion campaigns may be needed.

Aquaculture may compete with other production systems on several levels. Supplies of labor, space, capital equipment, and financing can be drawn from a common pool. Competition for facilities is likely to be most severe at the local and regional level, although production destined for a

distant urban or export market may encounter critical shortages or congestion in other parts of the economic system. Even if there is no immediate physical conflict with capture fisheries over the use of ponds or brackish water inlets, conflicting ownership claims are likely to arise if the aquaculture activities add value to property. The cultured product is in direct competition with fish or shellfish harvested from the wild, and in less direct competition with other foods, particularly those high in protein. Transportation and marketing systems are generally used by producers of all food items, as well as by other production sectors of the economy.

The circumstances and perceived needs that lead to the development of aquaculture may change over time. An aquaculture project may be a temporary solution to local problems but may not be viable over the long run. Viability depends not only on economic profitability but also on the role the project plays in the community. Customs and traditional power structures are likely to be more important than written laws in determining how an aquaculture enterprise operates. Customs ranging from socially accepted pilfering to traditional labor roles for segments of the community will influence the organization and operation of any project.

Where the regional government is responsible for the maintenance of roads and communication systems, the operation of extension services, hatcheries, and other facilities can be organized on a regional or national basis. National governments determine the formal structure of laws and regulations, and national development plans may be critical for encouraging or discouraging aquaculture relative to other activities. Other policies — such as differential exchange rates, provision of credit facilities, educational systems, participation in regional trade groups or activities sponsored by international agencies, and the economic and technological infrastructure — are important considerations in development planning.

Problems

A major goal of food development programs is to improve the nutritional well-being of the population. Another goal is to increase local income levels with the assumption that people will use this increased income to improve their standard of living — better food, medicine, education, and housing. However, people sometimes spend the increased income on products or activities considered frivolous or nonproductive by the planners.

In the choice of growing, harvesting, and processing techniques, the needs of the community should be considered. For example, in regions with high levels of unemployment, a labor-intensive technology might be selected despite the fact that it is neither biologically nor economically the most efficient from a business standpoint. Conversely, if some sectors of the population are suffering severe protein shortages, a technology that produces the largest volume of fish in the shortest period of time may be selected, with other means developed to address the unemployment problem.

In some developing countries, labor may be so abundant that the marginal productivity of labor in agriculture or fishing is near zero: taking away some workers from traditional activities and putting them to work on aquaculture may not decrease productivity in the rest of the local economy. In

This pigpen feeding area was deliberately built on the edge of an aquaculture pond on a farm in Costa Rica's Limón province. The floor is slanted so manure that falls there can be scraped or washed easily into the pond, supplying nutrients. However, too much manure causes an overabundance of microorganisms, which reduce the growth rate of the fish by lowering the pond's oxygen content. In this case, the pond has just been drained. Considered too nutrient-rich for a new crop of fish, the pond was planted with water spinach. (Photo by Bob Mack, New Alchemy Institute)

Small fish ponds near dwellings like these in the "atomistic" town of Teacapan, Mexico, could help families through periodic food shortages. (Photos by J. R. McGoodwin)

other situations, however, the amount produced by labor in the new aquaculture project must be assessed in terms of loss of productivity from other activities. For example, in a Philippine community the change from capture fishing to seaweed farming resulted in a decline in fresh fish landings. The scarcity of fish contributed to a tripling of local fish prices over a year.

In some areas, farmers may be unwilling to deal with fish, while a traditional fisherman may feel that aquaculture is a form of farming and that engaging in it would damage his image. Another potential labor problem is that high-paying managerial jobs may be filled by imported labor, causing local resentment and possible economic conflict. If the types of jobs required by the aquaculture project are not attractive to the local population, labor may have to be imported to fill even low-skilled jobs. A large influx of labor is likely to create local social and economic changes, some certain to be disruptive.

Although fish provides calories, it is usually expensive compared to other caloric sources, so its major importance is likely to be as a source of high-quality protein. We must ask first whether the local population needs additional sources of protein. If so, is aquaculture the best way to provide this? And, is the need for protein distributed throughout the population, or is it specific to groups, such as children or nursing mothers? Another issue is whether the type of fish or shellfish protein provided by aquaculture is acceptable to local palates. Taboos in many parts of the world militate against acceptance of any kind of fish as food; other taboos simply prohibit certain species or species groups (see *Oceanus*, Vol. 22, No. 1, p. 67). In the Nilote and Bantu tribes of East and South Africa, for example, fishing or eating fish can lower one's social status, since fish are considered to be unclean food. All such questions call for care in planning an aquaculture project.

Aquaculture projects may be designed to provide profits to either a private owner or the community at large. Local people may receive little or no benefit from a profitable project unless taxes collected from the enterprise are used within the community for such projects as improved schools. But even if accomplished, this circuitous return may not be perceived by the local residents as a consequence of aquaculture. If the project were owned by the municipality, there could be improved services for all local residents in the same way that an enterprise owned by a cooperative or association benefits members of the cooperative.

When private enterprise is fostered in regions where the distribution of capital is unequal, a project can result in increased social stratification. In many cases, projects are restricted to residents who can afford an initial investment, so the only individuals who can effectively take advantage of the new opportunity are those who are already well off. In Nigeria, for example, most farmers who enter aquaculture are already well established. If this kind of situation is deemed undesirable by the project planners, methods of extending credit to the needy should be investigated.

An aquaculture project may produce benefits that are more widespread than the provision of food. For example, an enterprise established with careful attention to marketing may develop new roads or communication lines to distribute the product; the same roads also would serve many other purposes. A processing facility developed in association with aquaculture could provide the means for processing other fish — those from open ocean or freshwater fishing. Credit systems designed for the aquaculture project may be expanded to include other development projects

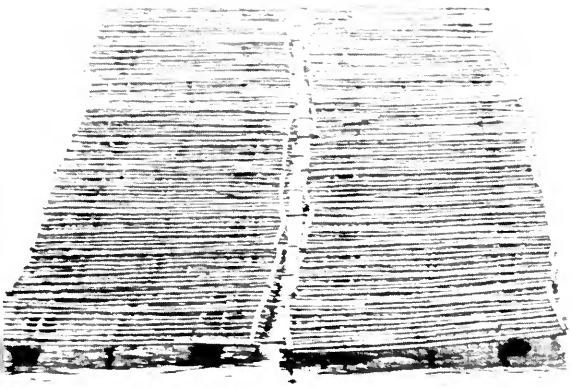
Harvesting Tilapia *from a drained pond at a Peace Corps project in Zaire. (Photo by Roger Palm, Peace Corps)*

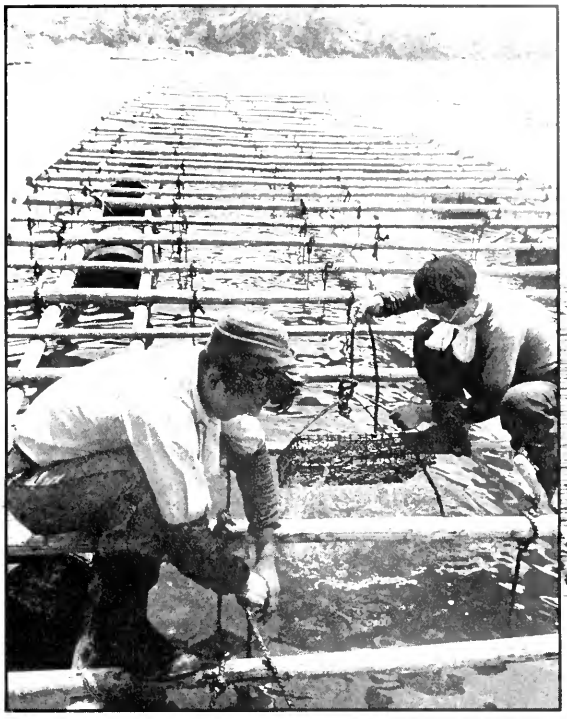
within the region and could lead to regional economic revitalization. Electric lines installed to run pumping equipment also could serve many other purposes in the community. Other indirect benefits may be trained labor and improved markets for fresh fish and other products. Indirect effects of an aquaculture enterprise are likely to be different in each situation. Careful assessment of the local economy would indicate which sorts of indirect benefits are most likely, and how the beneficial effects could be intensified.

There are strong arguments for the culture of native species: markets for the products already exist, as do approved methods for handling and transporting the fish; local scientists are likely to be familiar with their feeding characteristics and growing conditions; and the problem of introducing a species that may become a pest in the natural environment is avoided. In Sierra Leone, the mangrove oyster (*Crassostrea tulipa*) grows wild on mangrove roots. But this species grows faster and bigger when suspended on underwater racks. The racks provide the oysters with a constant flow of nutrients that their crowded cousins in the wild must do without at low tide. Harvested, steamed, shucked, and heat-sealed in plastic bags, these cultured oysters bring a higher price than wild ones at local markets.

However, if the cultured products do not have distinct advantages over those from the wild — such as superior quality or availability over a longer season — competition with harvest from the wild may keep selling prices too low to cover a project's expenses. The choice of a species similar to native species may allow an aquaculture project to take advantage of existing markets and improve efficiency, too. For example, cultivated varieties of native species may have faster growth or may be disease resistant. A cultivated species that is similar to native species may be particularly desirable for government projects intended as demonstrations of the potential of aquaculture. If a project is being run on a strictly profit-making basis, a species intended for a high-priced, specialized market would be the best choice, and this may or may not

Aquaculture is already a tradition in many Asian societies. At this Japanese oyster farm (right), the mollusks are grown in wire cages suspended from rafts. (Photos courtesy of Consulate General of Japan, New York)





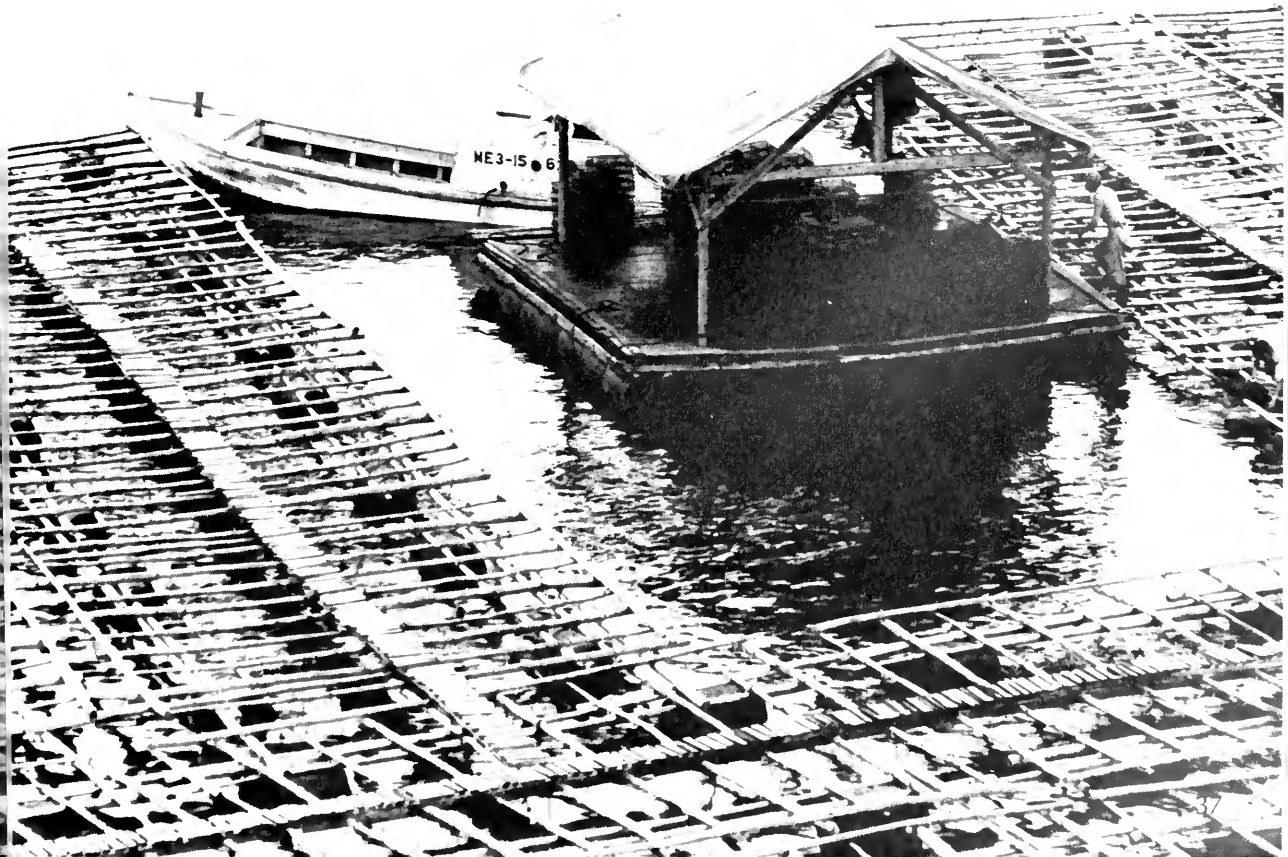

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Table 1. Aquaculture species cultivated in Latin America

Water Type	Species	Country
Freshwater (cold)	Trout (*Salmo* sp., *Salvelinus fontinalis*)	Mexico, Venezuela, Colombia, Brazil, Peru, Argentina
Freshwater (warm)	Boco chico, Coporo, Curimata (*Prochilodus* sp.)	Colombia, Brazil
Hatchery programs	Mackerel (*Basilichthys bonairensis*)	Brazil, Chile, Argentina
	Tilapia (*Tilapia* sp.)	Mexico, Brazil, Costa Rica
	Ornamental fish	Brazil, Venezuela
Cultivation in lakes	Bagre de canal (*Ictalurus punctatus*)	Mexico
	Tilapia (*Tilapia* sp.)	Mexico, Brazil, Paraguay
	Freshwater shrimp (*Macrobrachium rosenbergii*)	Honduras
Brackish or salt water	Mugilidos (*Mugil* sp.)	Colombia, Brazil
	Shrimp (*Penaeus* sp.)	Mexico, Costa Rica, Panama, Brazil, Ecuador
	Mussels (*Mytillus* sp., *Perna perna, Aulacoyma ater*)	Chile, Venezuela
	Oyster (*Crassostrea* sp.)	Venezuela

Source: Manuel Martinez, 1982. The role of non-technical factors in the development of Latin American aquaculture. In *Aquaculture Development in Less Developed Countries: Social, Economic, and Political Problems,* eds. L. J. Smith and S. Peterson, p. 57. Boulder, Colo: Westview Press.

be an introduced species. (The disadvantages of introducing exotic species was discussed in an article drawn from experiences with the introduction of the Japanese oyster [*Crassostrea gigas*] around the world — see Oceanus, Vol. 22, No. 1, p. 29).

Institutional Support

In Asia, a long aquacultural tradition mitigates the social and economic dilemmas that typically arise when aquaculture is introduced to a community. There is now great interest in developing aquaculture in many parts of Latin America (Table 1) and Africa. For example, successful introductory projects have been conducted in Sierra Leone (raising mangrove oysters) and in Costa Rica (Tilapia).

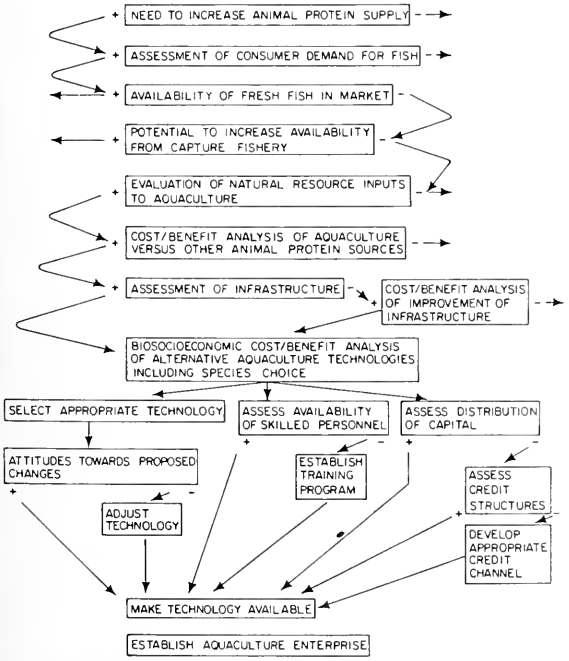
In developing countries, some rural communities, such as in Mexico, have lost their traditional subsistence systems and have become dependent on wage labor without acquiring the organizational structures that bring workers together in other societies. In these "atomistic"

societies, the mutual dependence of household members and the distrust of all others (even most other relatives in the community) create a situation in which the appropriate scale for aquaculture projects would be the household. Culturing fish could become a productive subsistence activity for these societies during the frequent lean times of unemployment. In contrast, Brazilian communities have had successful experience with sharecropping contracts in agriculture and fishing, integration of agricultural production and industrial processing, community cooperatives, and government-organized agricultural systems. These suggest a potential for aquaculture enterprises organized by the national government or operated as cooperative community activities.

Aquaculture development projects are sponsored by a range of donor agencies: private enterprises, private charitable foundations, government aid organizations, intergovernmental aid organizations (especially the United Nations' Food and Agriculture Organization), national governments, and state governments. Each of these organizations is likely to have different goals for its projects and different approaches to the introduction of a project to a community.

Awareness of community needs and community political structure varies greatly from project to project. Private enterprises, usually intent upon making a profit, may be the most careful planners of development projects because the cost of failure is felt immediately by the individuals who have organized the undertaking. In contrast, financial viability is not the sole mark of success for a government agency; the effort of development may result in lasting benefits for the community even if the aquaculture project itself is short-lived.

Successful aquaculture development depends not only on good luck and good weather, but also on the careful consideration of technological, scientific, economic, and cultural factors. Such consideration was inadequate in many past aquaculture projects, but background research well in advance of any future projects may help developers avoid some of the pitfalls that have beset the earlier ventures. Project planners should at least assess the availability of labor, the acceptability of the product, and the suitability of the project's physical site and financial structure. Under appropriate circumstances, carefully planned aquaculture projects can make a substantial contribution to the well-being of people in the developing world.



Decision points in implementing aquaculture. (From Elements in Evaluating Success and Failure in Aquaculture Projects by R. B. Pollnac, S. Peterson, and L. J. Smith in Aquaculture Development in Less Developed Countries, *eds. L. J. Smith and S. Peterson. © 1982. Westview Press, Boulder, Colo.)*

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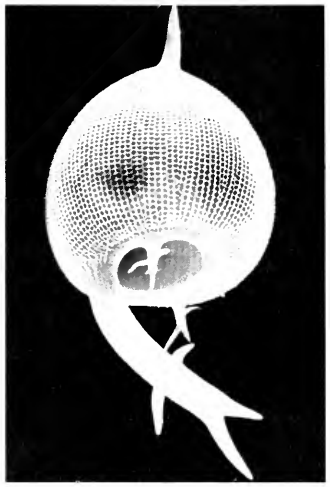
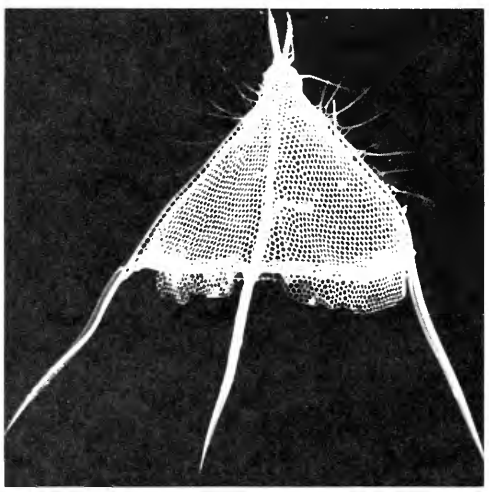
Minute Marine Organisms Found in Tropical Oceans

These Radiolarian Skeletons Are Made of Silica

Electron Microscope Photographs by Kozo Takahashi



Euphysetta elegans, x280



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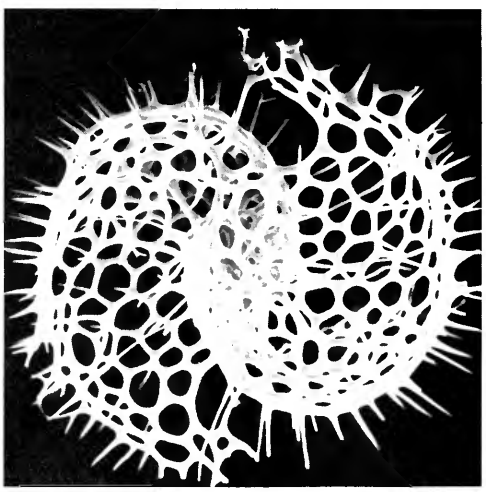
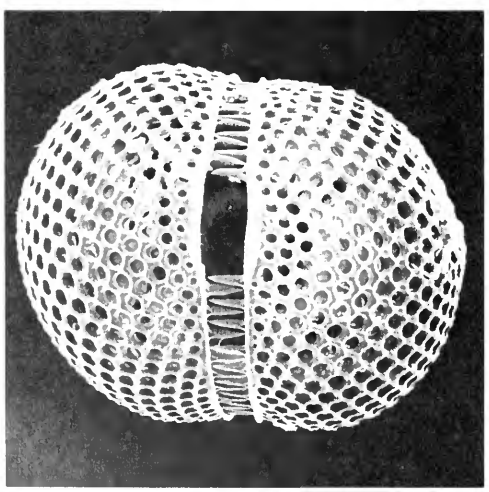
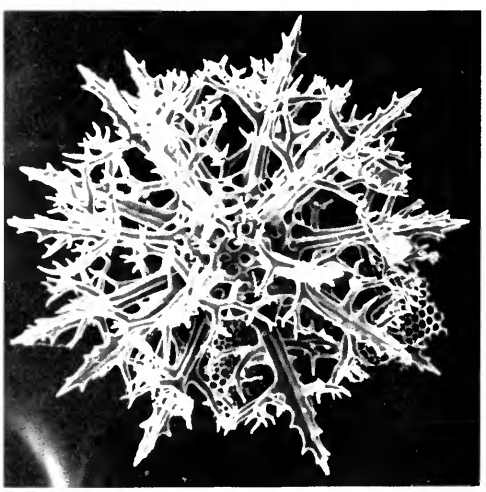


Larcospira quadrangula, x190



Conchellium capsula, x190



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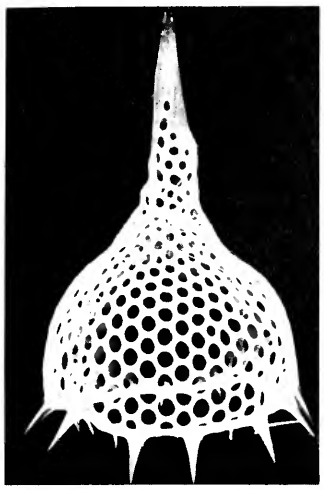

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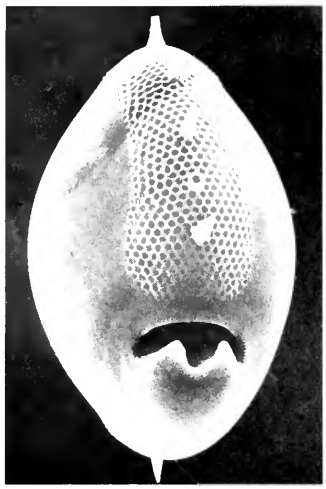

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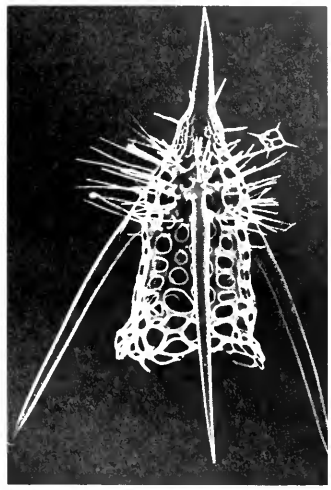

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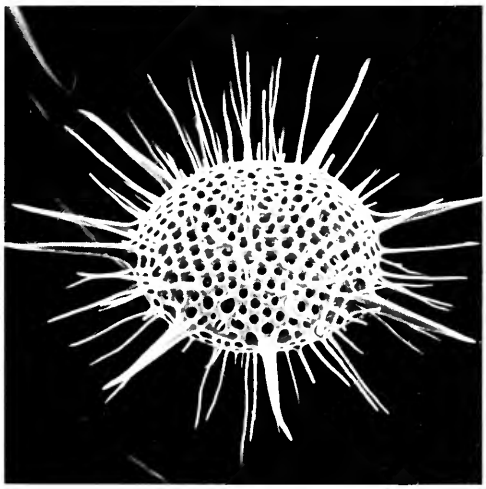

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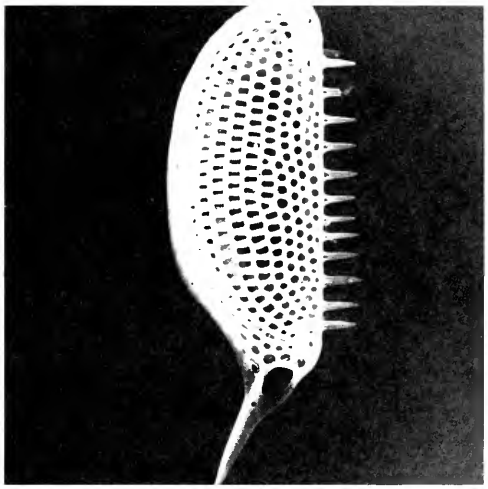
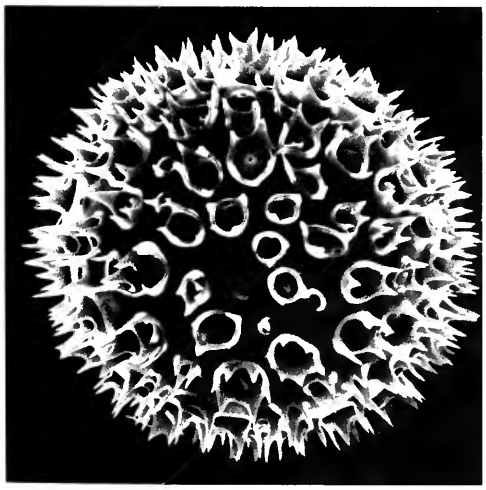
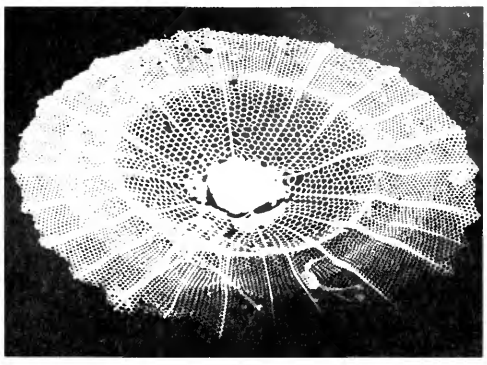


Conchidium caudatum, x170



Acrosphaera murrayana, x290



Theophormis callipillium, x120

Source: Kozo Takahashi, 1981. Vertical Flux, Ecology and Dissolution of Radiolaria in Tropical Oceans: Implications for the Silica Cycle. Ph.D Thesis, Massachusetts Institute of Technology-Woods Hole Oceanographic Institution WHOI-81-103.

The Subseabed Disposal Program for High-Level Radioactive Waste —

by John E. Kelly
and Cordelia E. Shea

In a departure from standard procedure, the Subseabed Disposal Program for high-level radioactive waste has initiated an innovative public participation process. Ordinarily, public participation begins after research has been completed. The subseabed program, however, is involving the public in the research phase in order to inform people of the program and to build consensus on the feasibility of subseabed disposal.

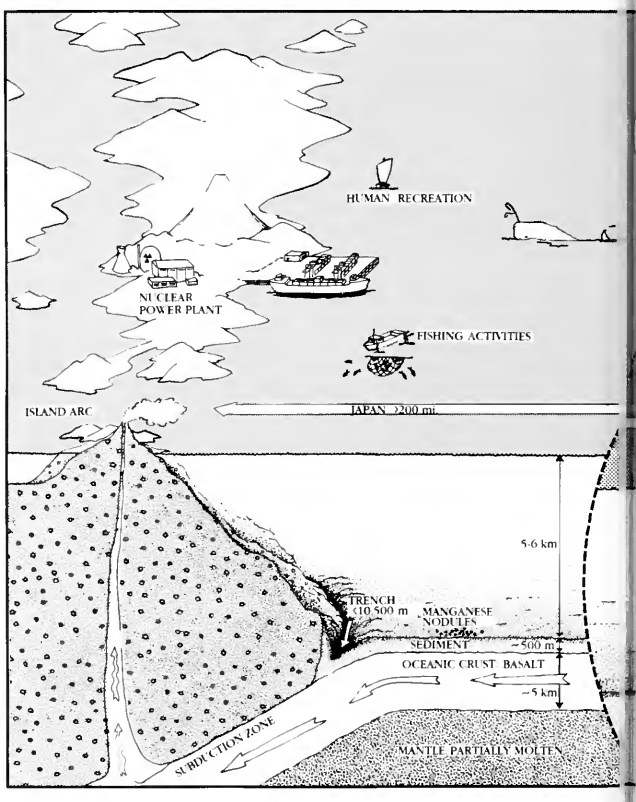
Subseabed disposal — the emplacement of radioactive waste canisters in sediments beneath the deep ocean — is being studied as a possible supplement to land-based disposal and as an international option. United States policy calls for waste disposal in mined cavities in basalt, tuffs (compacted volcanic fragments), salt, or granite as the primary option. For small countries with limited land alternatives, subseabed disposal is the primary option. If such disposal proves feasible, then continuing public participation through subsequent phases of the program will build consensus on how it should be developed within the context of both domestic and international policy.

The subseabed public participation process divides the public into four representative sectors: the research community, public interest groups, industry associations, and government decision-makers. The first step in the process is to educate these sectors about the program through publications, briefings, conferences, and other media. Response to these presentations points out public concerns and issues that should be addressed in the research phase.

In the second step, workshops for representatives of the four public sectors and scientists in the program will be convened to establish the criteria for determining whether subseabed disposal is feasible. If subseabed disposal proves feasible, then open meetings, involving a broad range of public and private interests, will be held to discuss how it should be implemented.

This process is designed to avoid the pitfalls of standard public participation procedure. Under the *National Environmental Policy Act*, the public is not involved until research on environmental impacts has been completed. At this point, the alternatives have been considered, sites selected, and blueprints prepared. The public, then, is asked to respond to draft plans and, in effect, to acquiesce to the overall design and construction of the project. Consequently, public objections to specific aspects of a project often are voiced as general opposition, and meeting those objections requires expensive modifications in the proposed project.

Through the subseabed public participation process, the public has the opportunity to ask specific questions and raise general issues early in the project. In response, the research agenda is being adjusted and alternative designs are being considered in light of those public concerns. The public also has the opportunity to contribute to the drafting of feasibility criteria which will be used to determine whether subseabed disposal should be implemented. This ensures that, if subseabed is



Public Response

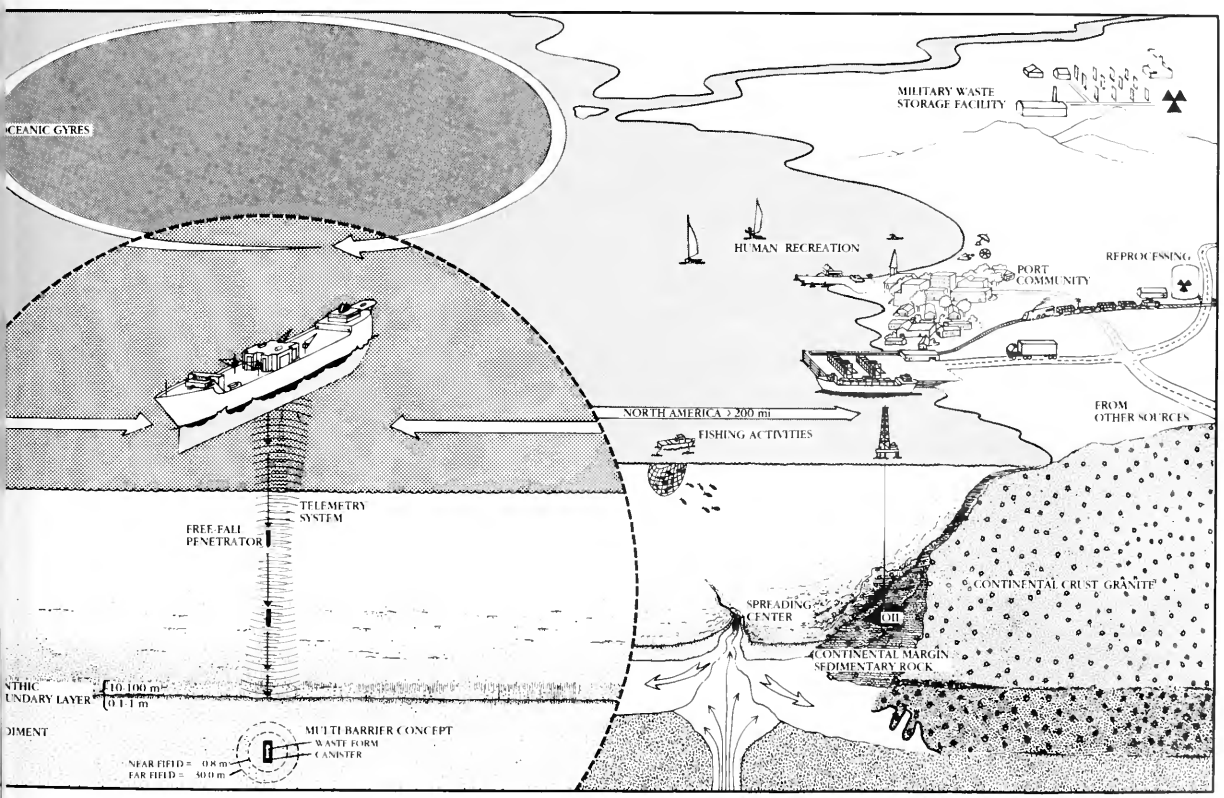
proved feasible, public discussion focuses on whether the criteria have been met rather than on the criteria themselves. This process, thus, improves the program and enhances the prospects for public acceptance in the long run.

This article is a progress report on the first step in the public participation process. Following background information, views of the subseabed program from the perspectives of the four public sectors are discussed. The report is based in part on presentations that we have made in collaboration with scientists connected with the program.

Background

The Subseabed Disposal Program for high-level radioactive waste focuses on commercial waste, though it may be applicable to defense waste as well. High-level waste is produced by defense programs and by commercial nuclear reactors. Under the Carter Administration, spent fuel from commercial reactors was considered waste that should be disposed of permanently, and fuel reprocessing was abandoned. Reagan Administration policy, however, calls for resumption of fuel reprocessing.

Commercial and defense wastes presently are stored at temporary facilities, awaiting development of permanent repositories. Spent fuel is stored in cooling pools at the reactors. Waste from past reprocessing is stored at West Valley, New York. Defense waste is stored in liquid and solid form at government facilities in Hanford, Washington; Savannah River, South Carolina; and Idaho Falls, Idaho. The volume of defense waste is far greater than that of spent fuel and commercial reprocessing waste, but the radioactivity as measured in curies is considerably less. Some of the waste generates heat as well as radiation. Though



THE SUBSEABED DISPOSAL CONCEPT: NOT TO SCALE

continued storage is possible, permanent disposal facilities for defense waste and commercial waste will be needed in the future.

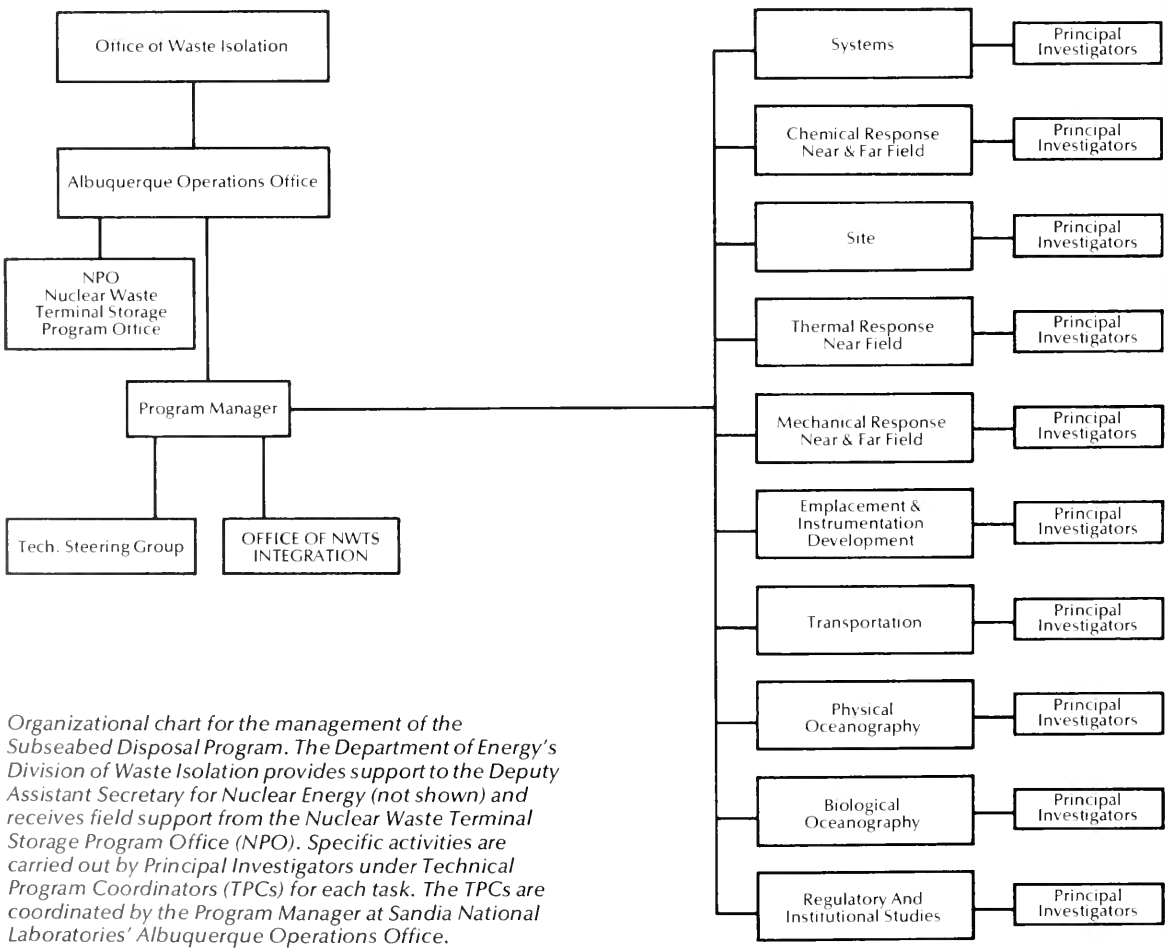
The Subseabed Disposal Program began in 1973 with a simple but fundamental idea: the search for an acceptable geologic medium in which to dispose of high-level radioactive waste should not be limited to the continents, but should include the other three-fifths of the world's geology that is covered by the oceans. After nine years of research, the concept of subseabed disposal has grown from an oceanographer's musing (see *Oceanus*, Vol. 20, No. 1, 1977) into a multidisciplinary project involving geologists, physical oceanographers, chemists, biologists, engineers, and social scientists. The program's primary objective, according to the published program plan, is "to assess the scientific, environmental, and engineering feasibility of disposing of processed and packaged high-level nuclear waste in geologic formations beneath the world's oceans."

Criteria for selecting subseabed study sites are 1) geologic stability and predictability, 2) the presence of sufficient sediment to isolate radioactive waste from the biosphere until it has decayed to innocuous levels, 3) the absence of valuable natural resources, such as commercial fisheries, hydrocarbons, or manganese nodules, and 4) remoteness from other human activities, such as surface vessel traffic and recreation. At this point, large areas in both the Atlantic and Pacific Oceans appear to meet the criteria. Scientists, however, will not select potential disposal sites until they determine whether subseabed disposal is scientifically and environmentally feasible.

The program schedule consists of four phases:

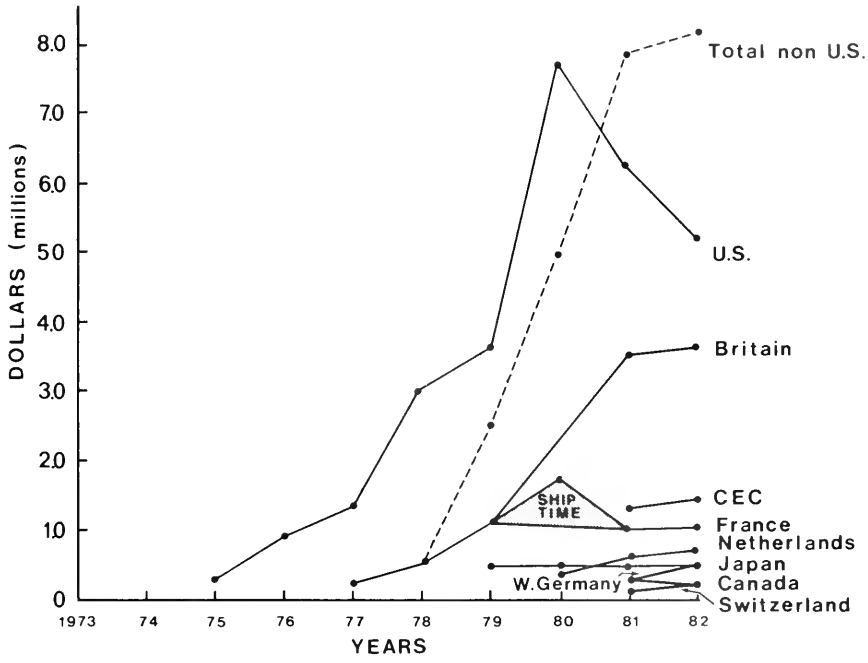
Phase 1 — Estimation of technical and environmental feasibility on the basis of historical data. Completed in 1976.

Phase 2 — Determination of scientific and environmental feasibility from newly acquired oceanographic and effects data. Estimated completion date: 1986-88 (depending on funding).



Organizational chart for the management of the Subseabed Disposal Program. The Department of Energy's Division of Waste Isolation provides support to the Deputy Assistant Secretary for Nuclear Energy (not shown) and receives field support from the Nuclear Waste Terminal Storage Program Office (NPO). Specific activities are carried out by Principal Investigators under Technical Program Coordinators (TPCs) for each task. The TPCs are coordinated by the Program Manager at Sandia National Laboratories' Albuquerque Operations Office.

A comparison of contributions to the Subseabed Disposal Program. "CEC" stands for the Council of European Communities.



Phase 3 — Determination of engineering feasibility and legal acceptability. Estimated duration: 7 to 10 years.

Phase 4 — Demonstration of disposal facilities. Estimated duration: 10 to 12 years.

The program is managed by Sandia National Laboratories, a government research facility operated by a subsidiary of American Telephone and Telegraph Company (AT&T), and funded by the Department of Energy's (DOE's) Office of Nuclear Waste Management. Unlike other disposal programs, however, most subseabed research is conducted by scientists at more than 20 universities and research institutions.

The international dimensions of subseabed research also distinguish the program. Other countries investigating subseabed disposal include Belgium, Canada, West Germany, France, Italy, Japan, the Netherlands, Spain, Switzerland, and Britain. Scientists from these countries comprise the Seabed Working Group (SWG) that was formed in 1977 under the auspices of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development. The SWG's annual meetings provide an opportunity for scientists to exchange data on their respective research programs, coordinate the use of research vessels and other specialized facilities, and discuss policy issues.

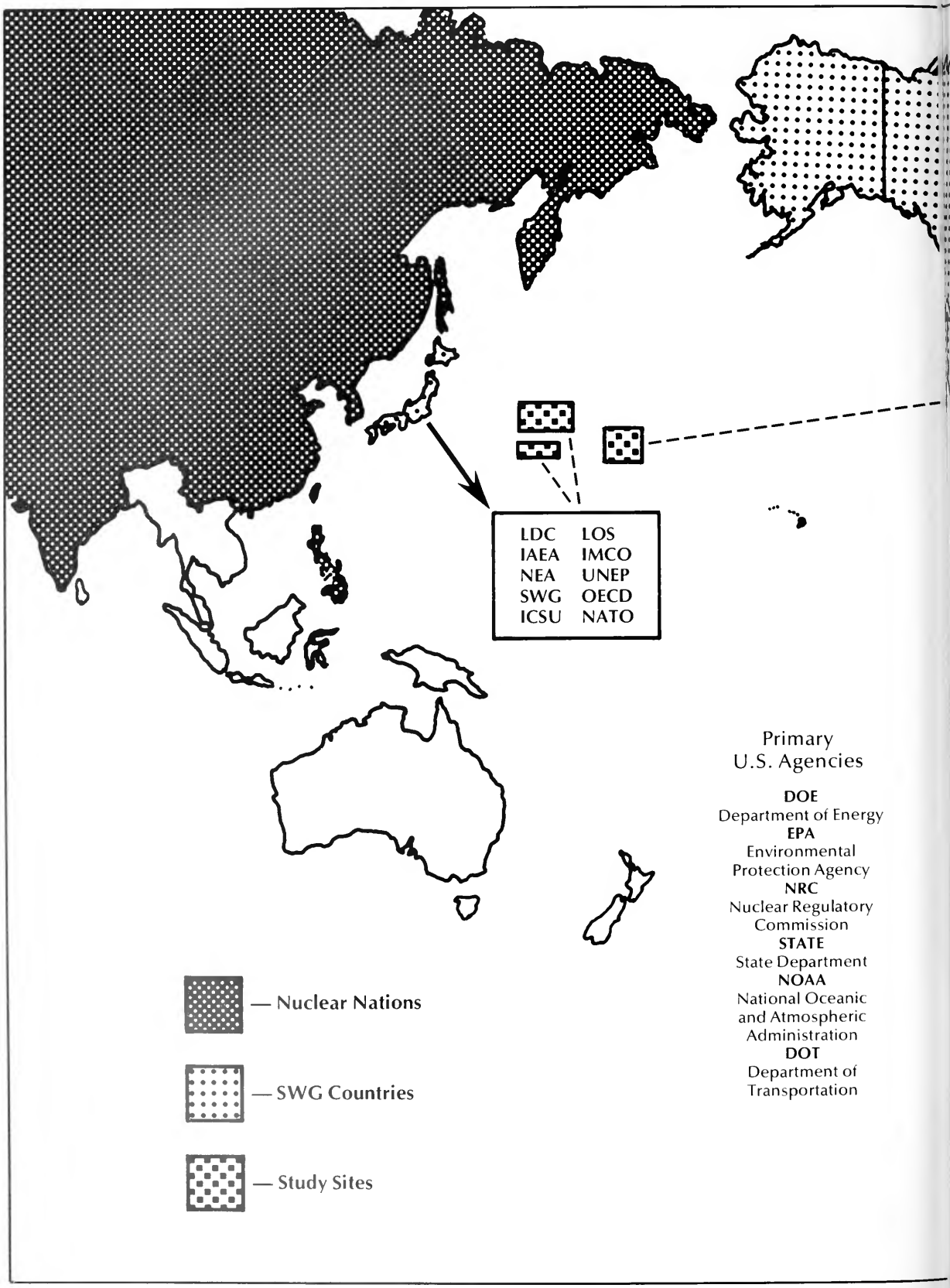
The interest of other countries is measured by their collective expenditures of more than $9 million on subseabed research in 1981 as compared to $6 million by the United States. For countries with limited land geology, subseabed disposal is considered a primary option. Britain, for example, reportedly will devote 100 percent of its nuclear waste research funds to subseabed disposal in 1983. A secondary objective of the U.S. program, therefore, is "to develop and maintain a capability to assess and cooperate with the seabed nuclear waste disposal programs of other nations."

Views of the Research Community

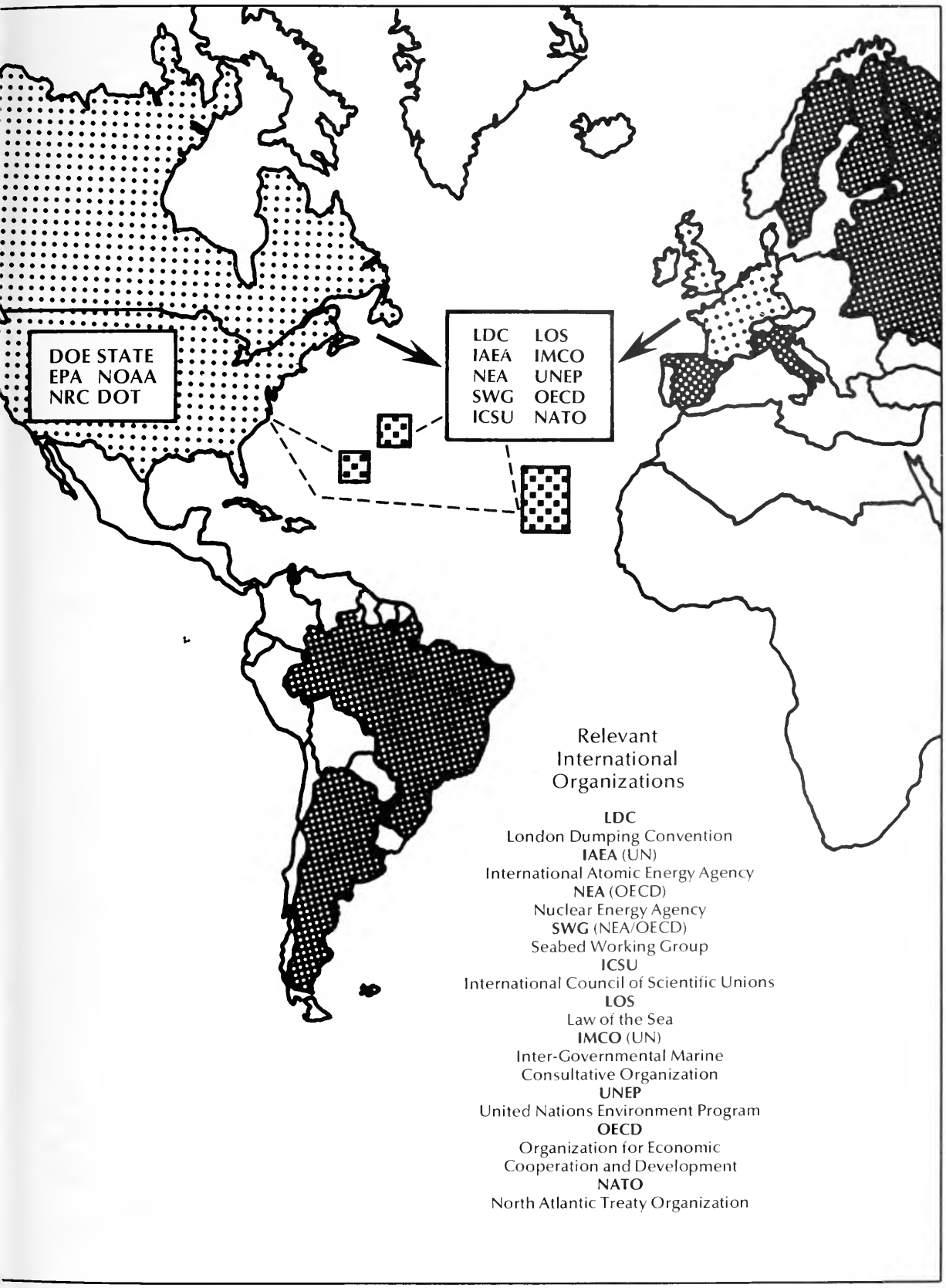
Peer review has been the cornerstone of the Subseabed Disposal Program. In 1975, review of the initial subseabed concept by a multidisciplinary panel of scientists laid the foundation for the program's research agenda. Since then, numerous workshops have been convened to develop and review research plans for specific aspects of the program. Scientists connected with the program have presented their research at conferences and have published their results in such magazines as *Nature* and *Science*. Three panels of the National Academy of Sciences have reviewed the program, and the International Council of Scientific Unions has conducted an international review. In addition, the program is reviewed semiannually by DOE scientists and managers. The Seabed Working Group also provides an annual review.

The peer review system performs two functions. First, it opens subseabed research to the criticism and refutation of the larger research community. Secondly, it points out possible problems that need to be studied. Continuing to

NATIONAL/INTERNATIONAL DIMENSIONS



OF SUBSEABED DISPOSAL RESEARCH



pass peer review, thus, builds consensus regarding the validity and completeness of subseabed research.

Views of Public Interest Groups

Public interest groups entertain a healthy skepticism toward the subseabed concept and the program. We have briefed members of major organizations, including the League of Women Voters, the Union of Concerned Scientists, the Center for Law and Social Policy, Greenpeace, and the Sierra Club. Many are unaware of the recent advances in oceanographic science and technology. At first, they place subseabed disposal in the Buck Rogers category of far-fetched technological fixes to social and political problems. Following an introduction to the basic concepts of oceanography and a description of the accomplishments and capabilities of such vessels as the *Glomar Challenger* and *Alvin* (see *Oceanus*, Vol. 25, No. 1, 1982), most realize that subseabed disposal is a serious, potential option and ask insightful questions. Many have expressed their appreciation for the program's avowed openness and desire for public comments and criticisms, yet the history of radioactive waste management, or mismanagement, has left a residue of distrust and ill will that tarnishes the subseabed program. Most importantly, they have expressed concern about specific technical and scientific aspects of the subseabed concept.

Scientific concerns focus on biological questions. In initial meetings, many people asked questions about the migration of radionuclides out of the sediment and the consequences of accidental releases into the ocean. They were concerned about the impact on ocean-floor ecosystems and about radioactivity moving through the food chain to the dinner plate.

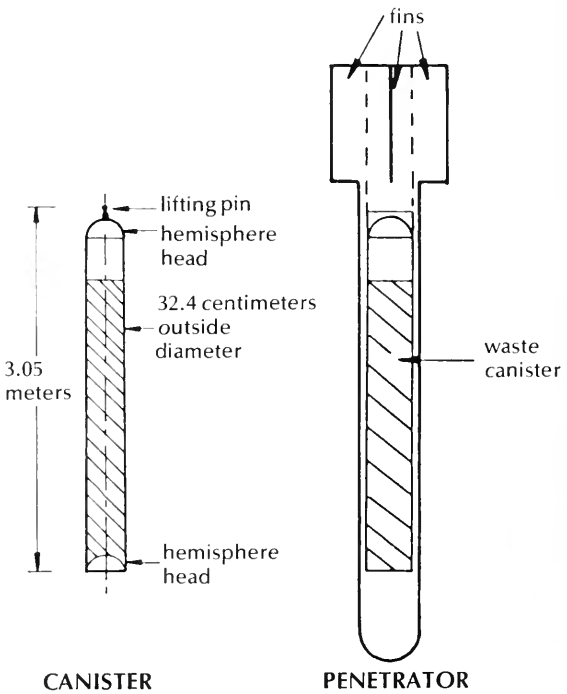
At the time, potential biological pathways could not be described precisely. Partly in response to these concerns, the biological research program was reviewed by outside scientists and will be further developed in coming years. This exemplifies how public concerns can influence the research agenda.

Technical concerns focus on the engineering dimensions, on how waste will be transported and emplaced in the sediments, and on what will happen if something goes awry. The program, however, has not entered the engineering phase, and will not do so until scientific and environmental feasibility has been determined. Nevertheless, preliminary transportation and emplacement design concepts are being developed.

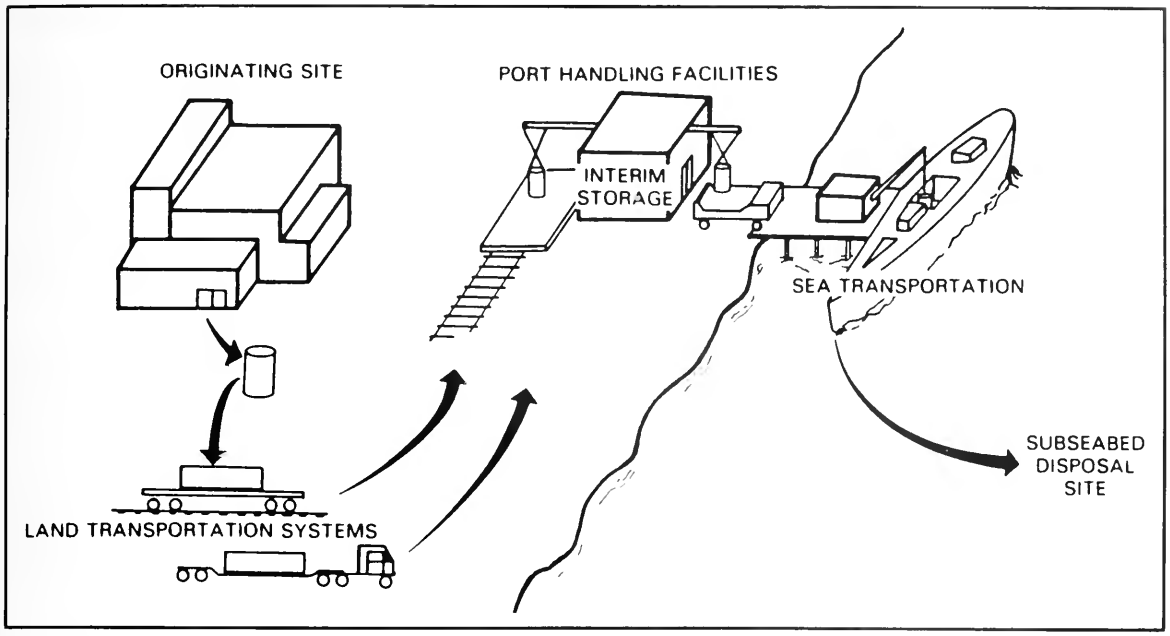
Retrievability is the basic concern in regard to emplacement. Possible emplacement techniques range from the free-falling penetrator to drilled holes. A penetrator is a pencil-shaped cylinder, about 3 meters long and .5 meters in diameter, that would fall through the water and embed itself in the sediment by the force of its own momentum. The program currently favors the penetrator method because it is the simplest. Drilled emplacement may be necessary, however, if penetrators cannot embed themselves sufficiently deep in the sediment. With either technique, disposal canisters can be located and retrieved if necessary using available technology.

The central concern in transportation system design is the port facility. If significant storage capacity at the port is required, then considerable opposition can be expected from local residents and public interest groups that have successfully opposed nuclear waste storage facilities of any kind for the last 10 years. This public concern will be a factor in the system design.

Public concern over system design creates a catch-22 situation for the program. On one hand, public interest groups say they need a description of a potential subseabed disposal system as a whole before they can evaluate the program. On the other hand, they express concern that current investment in the engineering phase may bias the scientific feasibility decision. From experience, they know that the momentum of a project can overwhelm the opposition, even if the arguments against the project are compelling. Yet they want, and the program needs, public involvement in the design



A canister containing radioactive waste could fit inside a penetrator, which would be dropped from a ship to penetrate the seafloor. (Drawing courtesy of Sandia National Laboratories)



Radioactive waste would usually have to travel by rail or highway to a port facility, from which it could be loaded onto a ship for subseabed disposal. (Drawing courtesy of Sandia National Laboratories)

process in order to develop an acceptable subseabed disposal system. Future workshops, therefore, will focus on system design concepts.

If we are not successful in our efforts to build a consensus on the feasibility of subseabed disposal, the program may be either stymied by public opposition or forced to resort to autocratic tactics that do justice to neither science nor the public interest. Furthermore, if scientists determine subseabed disposal to be infeasible, they may need public support to prevent it. The relationship between the program and environmentalists, therefore, is an uneasy partnership which can be instructive to both parties.

Industry Views

If the public interest groups are skeptical of the Subseabed Disposal Program, then the nuclear industry is downright suspicious. We have briefed representatives of major industry groups, including the Edison Electric Institute, the American Nuclear Society, and the American Nuclear Energy Council. In general, they were less receptive to our presentation than were the public interest groups, but were similarly unaware of present oceanographic capability. The scientific merits of subseabed disposal did not interest them. "Don't tell us about the technical details," they said, "this is politics."

Industry's concern about the politics of waste management is understandable. They believe that the technology is available for safe waste disposal in land-based repositories. The problem, as they see it, is that no one wants a repository built in their "backyard." The solution would be to force Congress to legislate the siting process so that someone will be forced to accept a repository.

Congress has been trying to pass nuclear waste legislation for many years but has been unable to do so for several reasons. No Senator or Representative wants a repository in his or her state or district. Sites under present consideration are in the West and South, and most nuclear reactors are in the Midwest and East. The equity issue of who accepts the risks and who enjoys the benefits, therefore, makes it difficult for any politician to ask his or her constituency to accept a repository, especially if it is the only repository in the country. Congress has nearly resolved this matter by relegating the siting decision to the President, while reserving the right to override his decision, and by adopting a regional repository scheme so that no state will be the only host, thus distributing the risk more equitably among the users of nuclear-generated electricity. But other issues must be resolved before legislation can be passed. The management of military waste and the construction of interim storage facilities for spent reactor fuel are sources of considerable debate.

With tentative agreement over siting provisions and other issues still pending, industry does not want anything to disrupt the legislative process. If subseabed disposal is seen as a viable alternative to land repositories, then Congressional

members from potential host states may be disinclined to accept a repository, and try to derail pending legislation or delay the siting process. DOE shares this concern, and the program has taken care to present subseabed not as an "alternative" but rather as a "supplement" or "complement" to land repositories. For example, after the first land repository is built in the West or South, a subseabed repository could be developed in the Atlantic Ocean as a regional repository. This would meet the disposal needs of the East Coast and address the equity concerns of western and southern legislators. Industry, however, sees no need for more than one repository and fears that Congress may perceive subseabed disposal as an alternative to a land repository in spite of their efforts.

Industry also is concerned with funding for the program. Under pending legislation, industry will be charged a set fee for waste disposal, and these funds will be used for research on and development of repositories. Since they feel that the technology for land repositories is available, industry sees no reason why it should have to support subseabed research, even if it may provide a less expensive disposal method. They contend that taxpayers should support such basic research and that industry funds should support only the actual development of repositories.

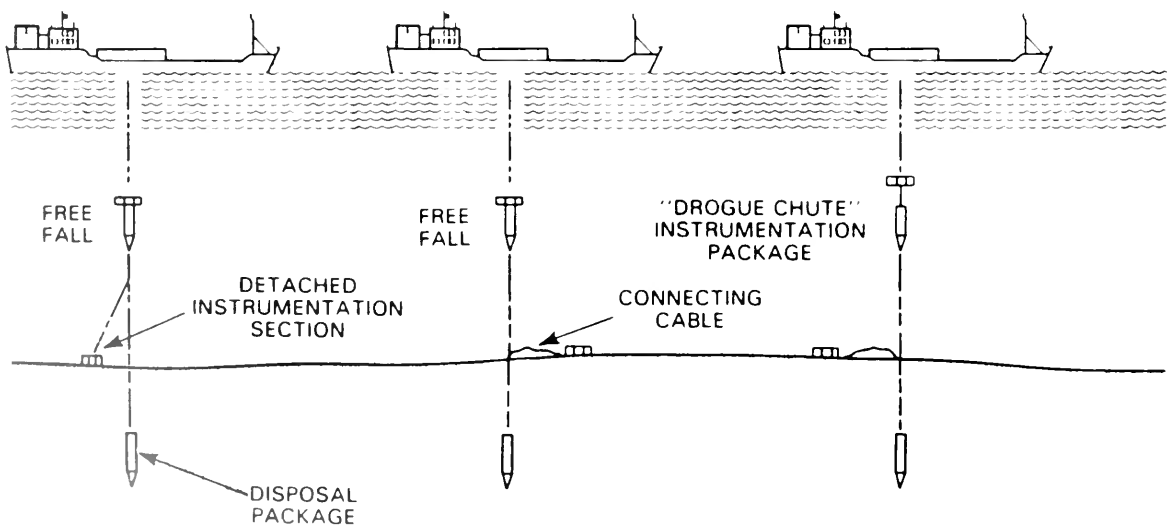
The federal government, however, is trying to eliminate unnecessary research programs. Therein lies another catch-22. If subseabed disposal poses an alternative to land repositories, then industry, DOE, and Congress may try to terminate the program for political reasons, as previously mentioned. If subseabed disposal is seen as redundant to land repositories, the Office of Management and Budget, Congress, industry, and DOE may try to terminate the program for financial reasons.

Congressional Views

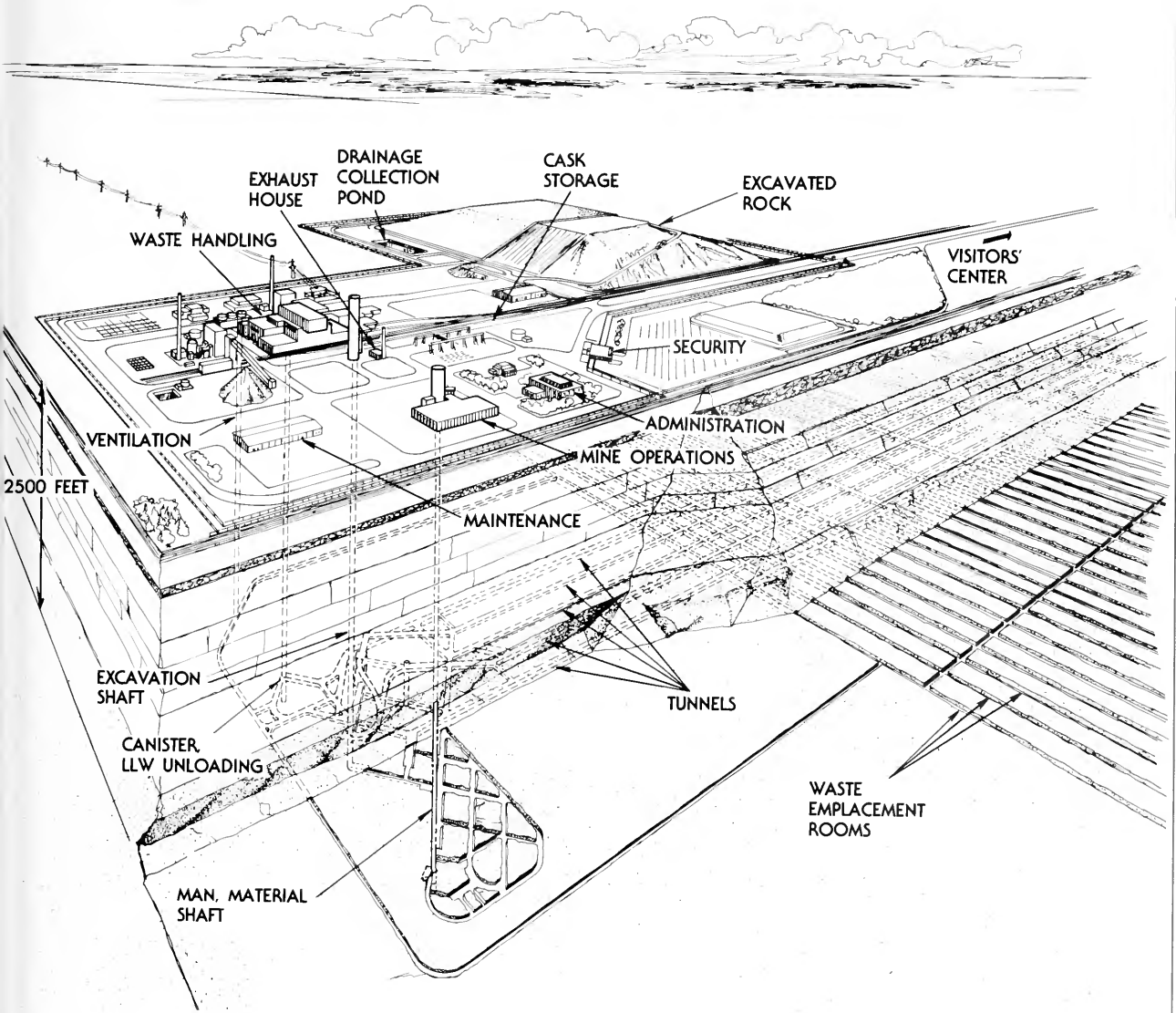
Most members of Congress and their staffs want to find a solution to the waste management problem. Their views on the appropriate methods differ, however, depending on their stand on nuclear power and on whether they are from a potential host state for a land-based repository. Despite these differences, only one Congressional staff member in more than 30 briefings has categorically opposed continuation of the program. Most were receptive to our presentations, and asked incisive questions.

Members of Congress and their staffs share industry's concern that the subseabed disposal idea could derail pending nuclear waste legislation by offering an alternative to land-based repositories. By the same token, they do not want pending legislation to foreclose potential options, including subseabed disposal. Frequently, they ask whether DOE supports the program, which it does with the caveat that subseabed disposal not be the primary option. They warn that the program is doomed without the department's support. On the other hand, many Congressional members and staff share environmental concern over biological pathways to humankind and protection of the oceans from pollution.

The legality of subseabed disposal is often questioned. Under the *Marine Protection, Research, and Sanctuaries Act,* Title I of which is known as the Ocean Dumping Act, the status of subseabed disposal is ambiguous at best. An Environmental Protection Agency (EPA) memorandum expresses the opinion that subseabed disposal is prohibited under the Act,



Three subseabed emplacement options. (Drawing courtesy of Sandia National Laboratories)



The land-based repository concept. (Drawing courtesy of U.S. Department of Energy)

which states that "no permit may be issued" for dumping high-level radioactive waste into ocean waters. Whether subseabed disposal would constitute "dumping" into the ocean is disputable, but the intent of Congress in explicitly prohibiting the issuance of permits for dumping high-level waste supports EPA's opinion. For subseabed disposal to be implemented, the Act would have to be amended.

International law also is ambiguous. Under the *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter,* commonly known as the London Dumping Convention, dumping of high-level radioactive waste is prohibited. The Convention defines "dumping" as "any deliberate disposal at sea of wastes or other matter from vessels, platforms or other man-made structures at sea." Again, whether subseabed disposal would constitute "dumping" is disputable. A National Oceanic and Atmospheric Administration memorandum expresses the opinion that subseabed disposal would not constitute "disposal at sea," but an EPA memo expresses the opposite opinion. The more pertinent point is that subseabed disposal was not discussed in any of the 1972 treaty negotiations because the concept had not been developed. In any event, some nations probably will insist that the

SDP—Definitions

Scientific and Environmental Feasibility *means that for a given emplacement scenario, it can be shown with a probability of better than Z that the maximum individual dose will be less than X and the population dose will be less than Y.*

Engineering Feasibility *means that for a given operational scenario, it can be shown with a probability of better than P that high-level waste can be emplaced as specified in the repository (and, if required, recovered) with a reliability of better than R.*

Proof of Concept (Operational Feasibility) *means that operation of a pilot-scale waste handling and repository system has been demonstrated with a reliability of better than R.*

Convention be amended before subseabed disposal is implemented.

If subseabed disposal proves feasible, then Congress will have to decide whether and how to legalize it under the Ocean Dumping Act. The United States also will have to respond to proposed changes in the London Dumping Convention. Such changes in our policy will be controversial. Though it is too early to initiate legislation at this point, working with Congress, public interest groups, and industry can establish the context for cooperation in the future.

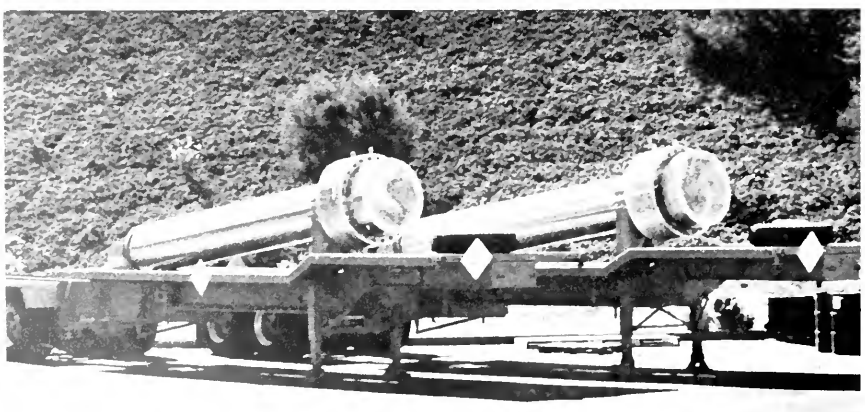
Educating Congress about the program has proved invaluable in regard to current legislation. Though under pressure to cut budgets and pass a nuclear waste bill, Congress has spurned attempts to phase out the program. The Senate has amended its waste bill to provide for the continuation and acceleration of alternative technologies, such as subseabed disposal. Had information about subseabed disposal not been provided, the program could have died in obscurity.

The Path Ahead

The Subseabed Disposal Program faces challenges in both the national and international arenas. To determine feasibility, the program must continue to make progress in its scientific research while building consensus on the definition of feasibility among a broad range of interests, both within the United States and among other countries. The first step in the public participation process is laying the groundwork for this task. The success of future workshops in building this consensus will indicate whether involving the public in the research phase of the program has been constructive.

In regard to feasibility, the illegality of subseabed disposal under the Ocean Dumping Act presents another catch-22 situation. Under the Act, EPA sets standards for ocean dumping of allowable waste. However, neither EPA nor any other agency can set standards for an illegal action. Without standards, feasibility cannot be determined in the usual manner. And until feasibility has been determined, Congress probably will not legalize subseabed disposal.

The workshops, therefore, must develop tentative standards for subseabed disposal. The following definition provides a possible framework for the standards: *Scientific and environmental feasibility means that, for a given emplacement scenario, it can be shown with a probability of better than Z that the maximum individual dose will be less than X and the population dose will be less than Y.* The standards are represented by X, Y, and Z, with "dose" meaning exposure to radioactivity released from a subseabed repository. If consensus on the



Two casks for shipping spent fuel from a nuclear reactor. Each cask is worth approximately $1.5 million. (Photo courtesy of U.S. Department of Energy)

standards can be established, then determining feasibility requires agreement on the emplacement scenario and its ability to meet the standards. In effect, the subseabed program is developing the tools for making that determination.

Consensus on the definition and determination of feasibility would provide the basis for Congressional consideration of subseabed disposal. Even if the United States legalizes subseabed disposal, however, unilateral implementation would be difficult if not impossible, especially beyond the 200-mile economic zone. International agreement on the definition and determination of feasibility, therefore, is necessary as well.

A modification of the U.S. process could be applied to the international context. The Seabed Working Group, like the United States program, is developing the tools for determining feasibility. Under an appropriate international body, such as the Nuclear Energy Agency or the International Atomic Energy Agency, consensus on the standards could be established and feasibility then could be determined. This would provide the basis for national decisions regarding amendment of the London Dumping Convention.

Scientific and environmental feasibility, however, is only the first step. Engineering feasibility also must be determined either by a similar process or, if subseabed disposal is legalized, by the appropriate national and international regulatory agencies. This will entail consideration of transportation as well as emplacement scenarios and the establishment of additional standards.

Public participation in these feasibility decisions ensures neither a positive nor negative result. Rather, it promotes rational decision-making, informed by science and tempered with politics. The success of the subseabed program depends as much on its mastery of this process as on the merits of its research.

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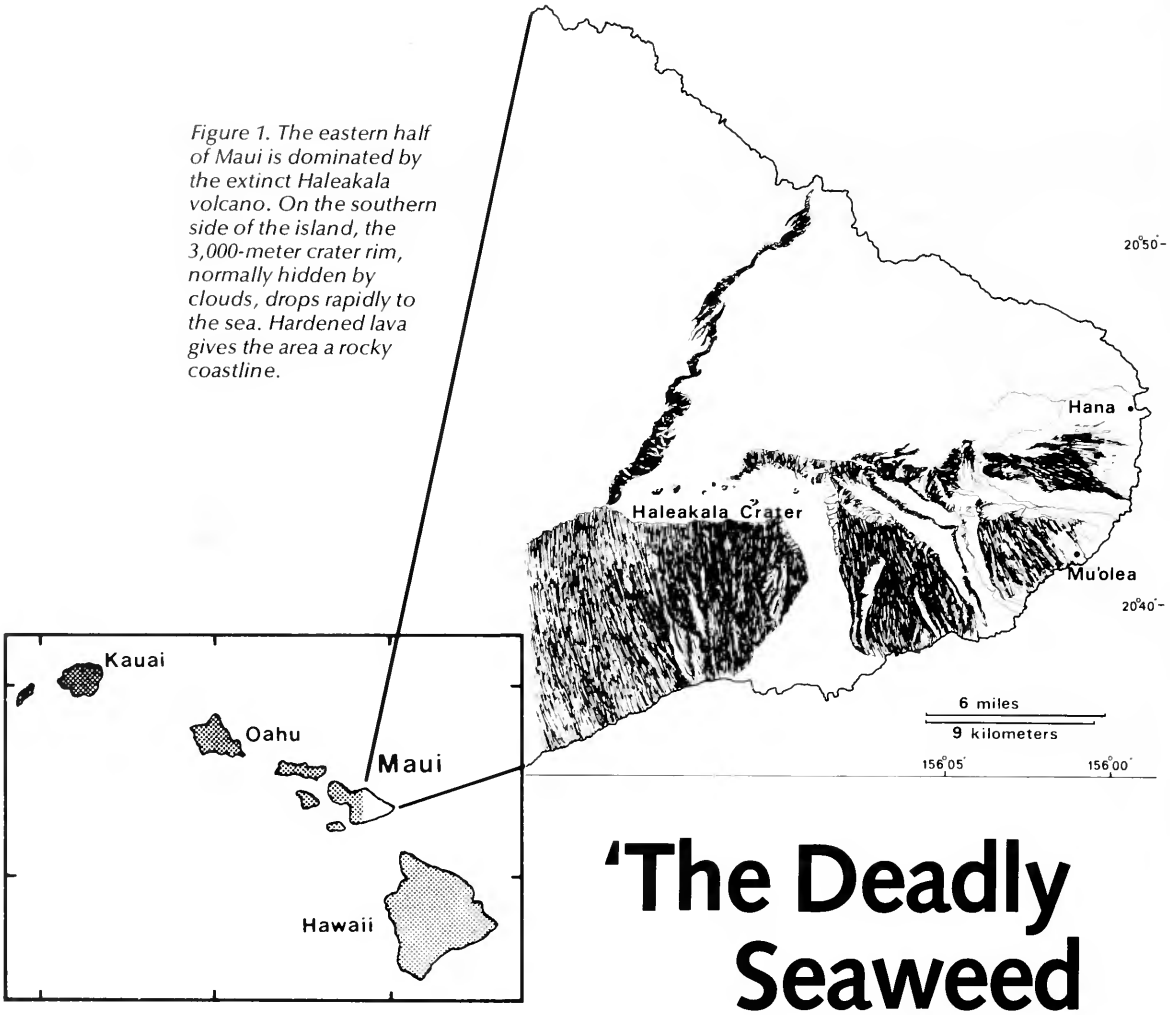

Figure 1. The eastern half of Maui is dominated by the extinct Haleakala volcano. On the southern side of the island, the 3,000-meter crater rim, normally hidden by clouds, drops rapidly to the sea. Hardened lava gives the area a rocky coastline.

'The Deadly Seaweed of Hana'

by Richard E. Moore, Philip Helfrich, and Gregory M. L. Patterson

The analysis of a poison from a rare marine organism long shrouded in myth and mystery has led to a discovery that could help increase our understanding of cancer and heart disease. The story of how an unusual molecule was isolated and finally identified is a case study of the winding, branching, unpredictable footpath known as scientific research.

Two decades ago, little was known about the origin of ciguatera, a human illness that can result from the ingestion of certain coral reef fishes. Researchers had noted that herbivorous fishes became ciguateric before carnivorous fishes, a fact that strongly suggested the causative agent, ciguatoxin, was of algal origin and was being passed on to carnivorous fishes through the food chain. It was the search for the responsible alga that prompted University of Hawaii research scientists to follow a lead provided by an entry in Pukui and

Elbert's *Hawaiian-English Dictionary* listed under *limu*, the Hawaiian word for algae and moss. The entry, *limu-make-o-Hana*, which translated means "the deadly seaweed of Hana," was a possible clue.

When Philip Helfrich finally found *limu-make-o-Hana* in 1961 at Mu'olea, south of Hana on the island of Maui (Figure 1), an examination of the organism disclosed that it was not a seaweed, but a coelenterate belonging to the genus *Palythoa*. Extracts of the coelenterate contained a powerful toxin. Although the physiological effects of the poison in mice were clearly not ciguateric, this discovery led the primary author down another trail. Slowly the mystery of *limu-make-o-Hana* began to unfold.

Geographical and Ethnological Background

Evidently *limu-make-o-Hana* had been known to the Hawaiians for a long time, but apparently they did not recognize its animal nature. In examining notes of 1920s artist Katherine Livermore, on file at the B. P. Bishop Museum in Honolulu, one could sense that the organism might have an animal-like character. She indicated that the *limu* moved when touched: "At Mu'olea . . . at the base of a 700-foot cliff in a tiny salt pool . . . grows this deadly *limu* on rocks. When touched the edges contract, changing from its natural dark gray color to a purplish hue and then it exudes a yellowish fluid, thus poisoning the water." Surprisingly, *limu-make-o-Hana* appeared to be restricted to a single tidepool below one of the steeply sloping flanks of Haleakala, a 3,000-meter extinct volcano (Figure 2).

This same pool is mentioned by David Malo, a chronicler of Hawaiian customs, in his 1903 book *Hawaiian Antiquities*: "I was told . . . that in Mu'olea, in the district of Hana, grew poisonous moss in a certain pool or pond close to the ocean. It was used to smear on the spear points to make them fatal. [The] men . . . who did the job . . . were called Hamohamo, the smearers. The moss is said to be of a reddish color and still to be found. It grows nowhere else but at that one spot."

The Hana region of Maui is sparsely populated, largely with people of Hawaiian ancestry. It was difficult for scientists to locate the pool because of a general reluctance of the Hawaiians to discuss the organism or its location. This secretiveness is pointed out in Livermore's notes: "In the time of the Kings,* this particular beach was tabu to the people and its location kept secret, as it was feared that people, knowing its location, might use it for evil purposes." The Hawaiian priests had placed the tabu on the area with a stern warning that serious harm and misfortune would befall anyone who disturbed the *limu*. At the time of the original collection, the scientists were warned by the local Hawaiians of the deadly nature of the *limu*. They said the organism would not only injure the collectors but also, by extension, bring them bad luck. Curiously, the first major collection was made on the afternoon of December 30, 1961; that same day, a fire of unknown origin leveled the Hawaiian Marine Laboratory housing the investigation.

When a second collection was made a short time later, the collector became ill as he gathered the animals from the pool. Inadvertently, he had exposed his bare hands and feet, which had numerous fresh scratches and abrasions, to the water in the tidepool. He noticed malaise as the water became "soupy and cloudy" with the mucous secretions of the injured coelenterates. He subsequently became dizzy and nauseous and acquired a headache with the increasing malaise. As the symptoms persisted, he was forced to visit a doctor who was unfamiliar with the syndrome and administered symptomatic therapy. The discomfort of his hands and feet continued for a week.

The Hawaiians have a legend to explain the origin of the toxic coelenterate. Livermore recorded the legend as it was told to her by one of the Hawaiian residents of Hana: "There lived a man in Hana who was most industrious and always seemed busily engaged in planting and gathering. Whenever the people around there went fishing, a person was always found missing on their return. This happened regularly, yet no one knew who to suspect. At last some of the men grew suspicious of him and, grabbing him, tore off his clothes and discovered on his back the mouth of a shark. They killed and burned him, throwing his ashes into the sea. At the spot where his ashes were thrown the poisonous limu grew."

Limu-make-o-Hana, known scientifically as *Palythoa toxica* (Figures 3 and 4), is one of the "soft corals" of the order Zoanthidae, of the class Anthozoa. The individual polyp is 20 to 25 millimeters high and 4 to 6 millimeters in diameter, with a tough outer epidermis in which sand grains are imbedded. In the Hana pool, it grows in a thick blanket, almost completely covering those portions that do not dry between tides. The tidepool appears to be above the tidal level of "highest high water" in the supralittoral zone on a basaltic bench. From our observations the pool could be classified to be in a heavy splash zone — at the highest tides some water breaks into the pool — rather than in a zone that is periodically inundated by waves.

Some physical and chemical parameters were recorded for the pool over a three-day period at four different tide levels in May of 1963. The data suggest some of the tolerances and ecological requirements of this organism. The pool is unshaded by nearby terrestrial vegetation, and its water temperature at low tide, when no water

*The monarchy ceased to exist in 1898.

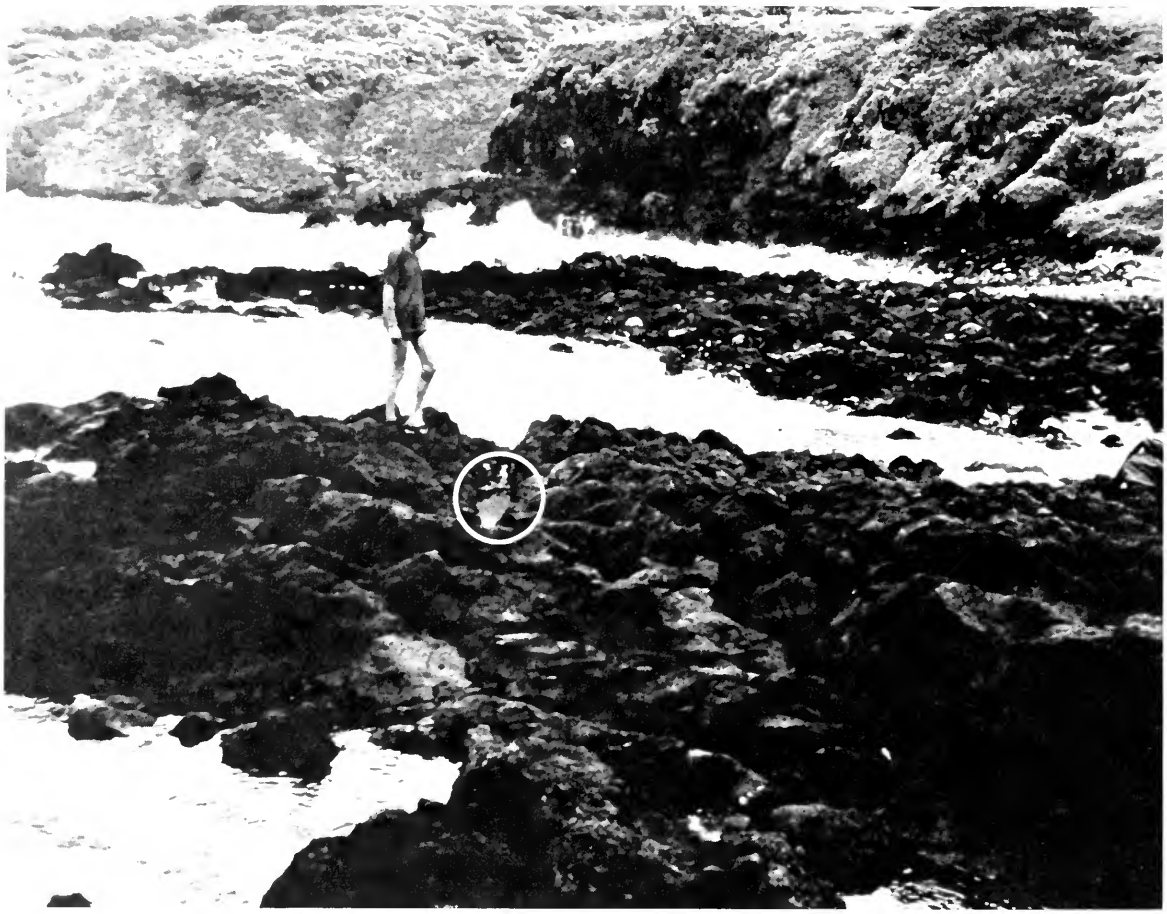

Figure 2. Limu-make-o-Hana *(the deadly seaweed of Hana) grows only in this small tidepool (center of photo) at Mu'olea on the island of Maui. The view is northwesterly towards Haleakala. Note the wave that has just passed, spilling a small amount of water into the pool. Ocean water enters the pool only at high tide. The onlooker is one of the authors, Dr. Richard Moore. (Photo by G. Bartolini)*

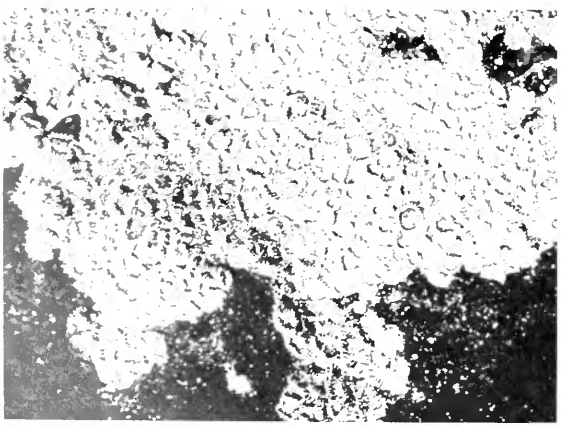

Figure 3. Polyps of limu-make-o-Hana *cover most of the bottom of the Mu'olea tidepool, which is about 20 centimeters deep at its deepest point. (Photo by S. Arthur Reed)*

exchange was taking place, was higher than that of the adjacent open ocean by 4 degrees Celsius.

The pool is in an area that is subjected to freshwater runoff, for the Mu'olea region is one of moderately heavy rainfall (average about 200 centimeters per year, with storms known to deposit up to 100 millimeters per hour). The rainfall in the area during the three-day period of observation was 1.83 centimeters, and the salinity in the pool ranged from 25.75 to 31.00 parts per thousand (the open ocean surface salinity for this area is about 35 parts per thousand). These observations suggest that *P. toxica* is a euryhaline and eurythermal zoanthid. It is thought to have survived in this location for at least three decades, and probably for more than 150 years, assuming this is the same pool described by Malo.

The oxygen content of the tidepool at low tide during daylight hours was relatively high, possibly indicating significant photosynthetic

Figure 4. Limu-make-o-Hana *is known scientifically as* Palythoa toxica. *The organism is not a seaweed, but a zoanthid, an animal belonging to the phylum Coelenterata. The more familiar coelenterates are the jellyfish, corals, and sea anemones. Coelenterates are characterized by the presence of stinging cells (nematocysts) in the tentacles. Palytoxin, the powerful poison in* P. toxica, *is not associated with the stinging cells. (Photo by R. L. Bowers)*

activity by algae (zooxanthellae) that live symbiotically in the tissues of these coelenterates. Several species of juvenile fishes that normally occupy supratidal pools in the Hawaiian Islands were found in the pool. These included a surgeonfish, a damselfish, a goby, and a blennie. The high concentrations of mucus that were released into the water when the coelenterates were harvested did not appear to adversely affect the fishes. No other macroinvertebrates were observed in the pool.

The Hawaiians also were aware that other species of *Palythoa* were poisonous. In fact some of these other species were considered to be sufficiently dangerous that the Hawaiians would at times fill the tidepools where they grew with sand, to prevent harm to swimmers and children.

In late 1961, a physician practicing in Hilo, Hawaii, recorded treatment of an eye injury that was attributed to accidental contact with the mucous secretion of an organism which the patient, a local Hawaiian, referred to as "*limu-make-o-Hana*." The causative organism, however, was a different species, *Palythoa tuberculosa* (Figure 5). Apparently the patient had been gathering opihis (edible limpets that are a delicacy to the Hawaiians) at Kaumomoa, about 10 miles southwest of Queen's Bath on the Kalapana coast of the island of Hawaii, when he sustained his injury. Unexpectedly, the implement that he was using to pry the shellfish from the rocks slipped into an adjacent patch of *P. tuberculosa*, causing some of the mucus in the animal to squirt into his eye. The marked edema of the cornea that ensued lasted for several weeks. According to the patient, the Hawaiians were quite familiar with *Palythoa's* harmful effect on the eye and used the juice of the beach morning glory (*Ipomoea pes-caprae*), which they called Pehuehue, as an antidote.

Figure 5. A colony of Palythoa tuberculosa *that contains the same toxin as* limu-make-o-Hana. *(Photo by G. Bartolini)*

It is interesting that *limu-make-o-Hana* was used to refer to a completely different species of *Palythoa* growing outside of the Hana district of Maui. One wonders whether the early Hawaiians could have intended *limu-make-o-Hana* to refer to all toxic zoanthids, since *hana make* means to kill and also has been used to denote a thing of destruction, such as a weapon.

Toxin Isolation and Identification

Animals could be collected from the Hana pool only once a year to allow for sufficient regeneration of the *P. toxica*. Attempts to grow the organism in other tidepools on Maui and Oahu failed. On the average, about 250 grams of wet polyps were obtained annually, yielding approximately 70 milligrams of pure toxin, palytoxin. On one occasion, however, five times more toxin was isolated from a collection made in the month of July. A scalpel was used to cut the coelenterates from the rocky substrate, and with the aid of a small sieve the polyps were transferred to an airtight jar containing aqueous ethyl alcohol to extract the toxin. The collector wore rubber gloves for protection from the poisonous mucous secretions that were released into the pool during the harvest.

Upon return to the laboratory, the aqueous alcohol, which had extracted most of the toxin, was decanted off and the zoanthids were extracted two more times. The ethanol in the combined extracts was removed by distillation at reduced pressure, and the aqueous concentrate that remained was washed successively with benzene and n-butanol to remove nontoxic fats and lipids. The defatted concentrate was then passed through a column of powdered polyethylene with water. Palytoxin was one of the few substances in the concentrate that was absorbed onto the polyethylene. A thorough washing of the column with water separated the inorganic salts and other nontoxic, polar organic materials from the toxin. The toxin was then readily removed from the polyethylene with aqueous ethanol. Subsequent ion exchange and gel filtration techniques removed remaining impurities, and pure palytoxin was isolated from *P. toxica* for the first time in April of 1963.

Characterization of the toxin, however, proceeded very slowly during the next several years. It was evident from the very beginning that palytoxin had a molecular weight in the low thousands and that its molecular structure totally lacked the familiar amino acid, sugar, and fatty acid building blocks commonly found in biomolecules of this size. This lack of repeating units, coupled with the limited availability of the toxin, made elucidation of the structure an exceedingly difficult problem. Chemical degradation always led to very complex mixtures that could not be separated with the chromatographic tools of the 1960s and early 1970s. Furthermore, the degradation products often

Nuclear Magnetic Resonance

The key technique in determining the elemental composition and structure of the palytoxin molecule was nuclear magnetic resonance (NMR) spectroscopy, one of several sophisticated methods scientists have developed for unraveling the mysteries of "inner space." NMR focuses on the structural relationships of a molecule's hydrogen atoms, but frequently the NMR spectrum is sufficient to determine the whole structure of an unknown compound. The unknown molecule is studied by placing it in a strong magnetic field whereby the nuclei of the hydrogen atoms behave like tiny magnets and tend to orient with the magnetic field, as compass needles do in the earth's gravitational field. The hydrogen protons, the positively charged particles in each nucleus, can be made to orient against the magnetic field, but energy, in this case radio energy, is required. A radio-frequency (RF) field is imposed on the molecule and either the RF or magnetic field strength is varied so that the different hydrogen nuclei can absorb RF radiation. The absorptions are detected by the NMR spectrometer and are printed out in a spectrum. The peaks in the spectrum represent the different hydrogen nuclei, which, because of their different arrangements in the molecule, require different energies for resonance.

had structures that could not be analyzed adequately with the technology available a decade ago. Structure work on palytoxin had to await the development of more sophisticated instrumental techniques, in particular high-performance liquid chromatography, for separating the complex mixtures resulting from the chemical degradation of palytoxin, and high-frequency proton nuclear magnetic resonance spectroscopy and field-desorption mass spectrometry, for determining the structures of the degradation products. The instruments for these tasks became available in the mid-1970s.

The molecular weight, 2,681 daltons, and the elemental composition, $C_{129}H_{223}N_3O_{54}$, of the palytoxin from *P. toxica* were not known until December of 1980, when the various units that were implied from the structures of the degradation products were assembled into a total structural picture for the toxin. Palytoxin proved to be a mixture of anomeric isomers which differed in structure around the 55th carbon. Two out of every three molecules had the structure depicted in Figure 6.

Palytoxin possesses 64 asymmetric carbon atoms. At this writing, the absolute configurations of 60 of the 64 chiral centers have been proposed, mostly from proton nuclear magnetic resonance and circular dichroism spectral studies of the degradation products and appropriate synthetic model compounds.

The structure of palytoxin is unique. The toxin belongs to an entirely new class of natural products. Its biogenesis is not at all obvious. There appear to be modified β-alanine units attached to a highly functionalized fatty acid chain that is 115 carbons long. Some of the nonadjacent carbons along this chain are interconnected by ether, ketal, and hemiketal linkages. There are no carbocyclic rings in the molecule. The C-9 to C-16 portion of the molecule might indicate incorporation of a monoterpene unit, but the five other methyl groups are not in isoprene arrangements.

Investigations of Related Organisms

Scientists in Japan have been engaged in an intensive study of *Palythoa* and palytoxin for over a decade. Their investigation, like the study in Hawaii, began as a result of a search for the origin of ciguatoxin. In screening toxic fishes from the Ryukyu Islands, the late Yoshiro Hashimoto and his associates at the University of Tokyo found that the filefish, *Alutera scripta*, contained a water-soluble toxin in the viscera that was clearly different from ciguatoxin. These studies had been prompted by reports in the Ryukyu Islands that the viscera of this fish frequently caused rapid death when fed to pigs and by the belief among fishermen in Saipan that ingestion of this fish sometimes induced vomiting, diarrhea, and aching joints in humans. Apparently the toxin, which Hashimoto named aluterin, was only associated with the viscera and not with the flesh of the fish. Examination of the gut contents of one of the toxic fishes revealed the presence of crushed polyps of a zoanthid that was identified as *Palythoa tuberculosa*. Later, aluterin was found to be identical to toxin from *P. tuberculosa* by direct comparison.

Structure-determination studies of the toxin from Okinawan *P. tuberculosa* were initiated by Yoshimasa Hirata, formerly of Nagoya University and now of Meijo University, and his colleagues in the mid-1970s. Independently, this group concluded in early 1981 that toxin from Okinawan *P. tuberculosa* has the same gross structure as the major component in the palytoxin from Hawaiian *P. toxica*.

A third independent discovery of toxicity in *Palythoa* was made by Leon Ciereszko and his students at the University of Oklahoma in the early 1960s. This group had been interested in examining the fatty acid esters and sterols of *Palythoa*

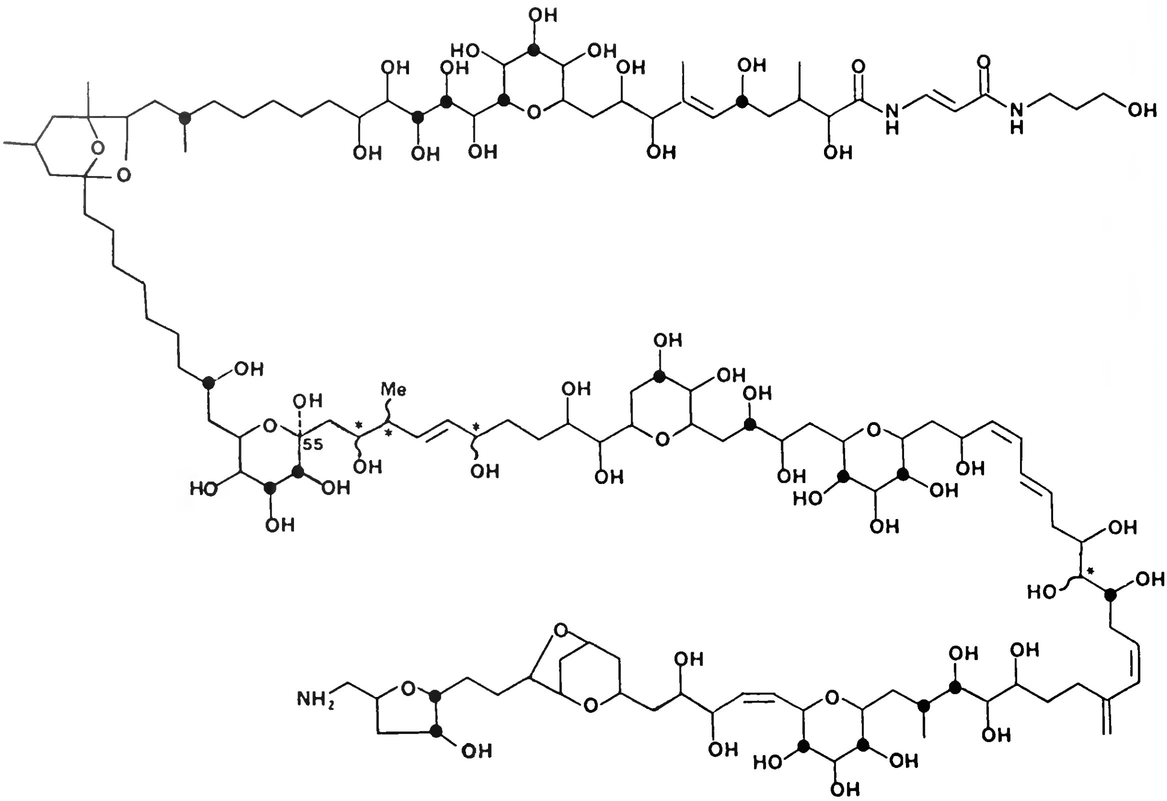

Figure 6. The structure of the major palytoxin molecule from Palythoa toxica, *including absolute stereochemistry of 60 of the 64 asymmetric carbons. The absolute configurations of C(57), C(58), C(61), and C(88), which are indicated by asterisks, are uncertain.*

caribaeorum from the Caribbean. A specimen of this coelenterate, a zoanthid that is similar morphologically to *P. tuberculosa,* had been collected in Jamaica in July of 1960 and was being processed for its lipids in early 1961 when the discovery was made. To prepare the coelenterate for extraction, one of the students had decided to pulverize the sun-dried animal in a blender. Some of the dust from this procedure leaked out into the atmosphere and the student and two others in the vicinity were accidentally contaminated. That evening all three persons became ill with chills, nausea, and headache. The next morning, however, the illness had completely subsided. Consequently, these researchers examined the organism for toxicity, whereby they found that the zoanthid contained a potent, water-soluble substance that was highly lethal to rabbits. Isolation gave a toxin that appears to be identical to the palytoxins from *P. toxica* and *P. tuberculosa*.

Palytoxin may not be confined to the genus *Palythoa*. G. E. Walsh and R. L. Bowers have described a toxic zoanthid that is not a *Palythoa*. In examining the new species, *Zoanthus kealakekuaensis,* which grows on lava rock in the intertidal zone of Kealakekua Bay on the island of Hawaii, a collector experienced temporary blindness and scarring of the cornea after accidentally getting some mucus from a polyp into his eye. The nature of this toxin has not been determined.

Origin of the Toxin

Palythoa toxica is highly toxic at all times of the year. The toxicity of *P. tuberculosa*, on the other hand, always shows a marked seasonal variation. This colonial coelenterate is highly toxic during the months of June and July and essentially nontoxic for the remainder of the year.

The Hashimoto group studied specimens of *P. tuberculosa* that were collected from Okinawa Island at different times of the year and noted that toxicity correlates with the number of egg-producing female polyps in the colony. The females, which appear in March and are present until September, begin to produce eggs in May. In one experiment, the eggs that were released from one of the female specimens were examined and found to be exceedingly toxic. Apparently the toxin is accumulated in the ovaries and other

reproductive tissues of the female polyps during maturation and is lost with ovulation.

The same observation has been made by the Ciereszko group for still another palytoxin-producing zoanthid, *P. mammilosa*, from Jamaica; toxicity appears to be associated with the egg-containing female polyps of this animal. The Oklahoma scientists also found that *P. caribaeorum* shows a seasonal variation in toxicity that is highest in June and July, though polyps of this zoanthid displayed high toxicity even when eggs were absent. Toxicity was not detected in *Palythoa* species collected in Bermuda and Florida in June.

The phenomenon of the association of toxicity with reproduction occurs elsewhere in nature. Another poisonous substance, tetrodotoxin, is found in the ovaries of pufferfish but is not confined to the reproductive organs. Toxicity varies markedly among individual puffers, and even in season the ovaries of some pufferfishes are nontoxic. Interestingly, cultured pufferfish are never toxic. Tetrodotoxin is also found in the egg clusters of certain western American newts of the genus *Taricha*. Yuzuru Shimizu, at the University of Rhode Island, has recently found that these salamanders lose their toxicity when reared in captivity. He suspects that biosynthesis of the toxin might actually be controlled by a microorganism in both the pufferfishes and the salamanders.

Although *P. toxica* does not show the marked seasonal variation in toxicity observed in the colonial species of *Palythoa*, polyps of *P. toxica* of the same apparent size and age were found to differ substantially in toxicity. A closer examination suggested a correlation between toxicity and bacterial count in individual polyps.

To test the possibility of microbiological involvement in toxin production, an examination of the bacteria associated with *P. toxica* was made. Bacterial cultures were prepared from homogenates of several polyps of *P. toxica*. The predominant bacterium was found to have a motile, curved-rod shape, approximately 0.5 by 2.5 micrometers in size (Figure 7). Ten clonal cultures of this organism, obtained from *P. toxica* collected in August of 1981, were prepared by standard plating procedures, using a growth medium consisting of 0.5 percent proteose peptone, 0.5 percent tryptone, and 4 percent sodium chloride adjusted to pH 8. This halophilic bacterium was found to be eurythermal and euryhaline and to utilize D-glucose either oxidatively or fermentatively.

Of the cultures prepared from clones, only one proved to be toxic. The toxin (35 micrograms) that was isolated from this single culture (100 milligrams of dried cells) was found to be identical in chromatographic behavior and toxicity with palytoxin. Insufficient material was available after purification for spectral characterization. Unfortunately, further attempts to produce more

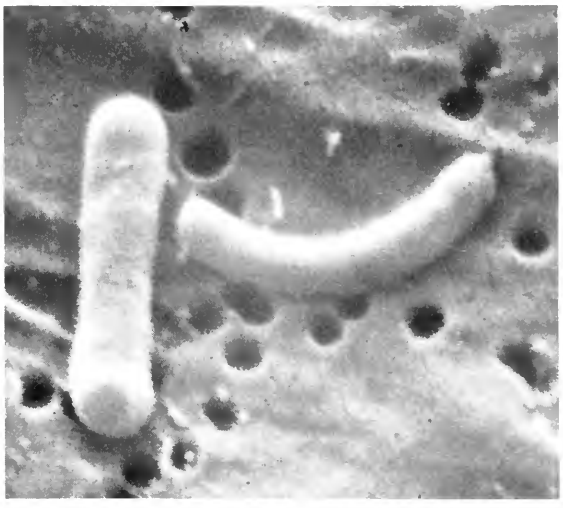

Figure 7. Scanning electron micrograph of the predominant bacteria observed in cultures from Palythoa toxica *polyps, magnified 26,500 times. (Preparation of sample and SEM photograph by R. Schneider)*

toxin from this or other clonal cultures have not been successful to date. One possible explanation for the observed variability in toxicity for the cultured bacterium is that the organism may attenuate, or lose its ability to produce toxin, quite rapidly after being removed from the host.

So, our preliminary evidence suggests that palytoxin may be produced by a bacterium in the coelenterate. The bacterium has not been rigorously identified yet, but its morphology is similar to *Vibrio*, a genus that is well known for its involvement in human diseases such as cholera. One of the more common marine species is *V. parahaemolyticus*, which is associated with many marine animals and is a major cause of human bacterial gastroenteritis. One of the hemolysins in this halophilic bacterium is a dialyzable, heat-labile, nonproteinaceous toxin. One wonders whether this latter toxin might be related structurally to palytoxin.

The illnesses that collectors and others have contracted in handling live, frozen, or freeze-dried *Palythoa* are probably due to mild infections by associated bacteria. Two of us suffered from a one-day, flu-like illness after handling a toxic *Palythoa* species that had been collected from a reef off Tahiti in May of 1964.

Toxicity and Pharmacological Properties

Palytoxin ranks among the most poisonous substances in nature. Although it is much less toxic than certain bacterial proteins such as botulinus and tetanus toxins, it is comparable in toxicity to ricin, a

polypeptide from the castor bean. It is one to two orders of magnitude more poisonous than batrachotoxin (found in certain South American tree frogs and used by natives on arrow tips), saxitoxin (one of several toxins associated with paralytic shellfish poisoning), and tetrodotoxin, and is presently the most powerful nonproteinaceous toxin known.

The intravenous lethality of palytoxin has been determined in several animals, namely the rabbit, dog, monkey, rat, guinea pig, and mouse, by investigators at the U.S. Army's Edgewood Arsenal in Maryland. Its average LD_{50} (the minimum lethal dose that will kill 50 percent of the animals tested) ranges from 25 ng/kg (nanograms per kilogram of bodyweight) in the rabbit, the most susceptible animal tested, to 450 ng/kg in the mouse. Palytoxin is slightly less toxic when administered by intraperitoneal, intramuscular, subcutaneous, and intratracheal routes, but is far less toxic when given by intragastric or intrarectal routes. Postmortem examinations of rats, rabbits, dogs, and monkeys receiving fatal doses show that palytoxin affects the cardiovascular, gastrointestinal, respiratory, and renal systems, and that it is an extremely hemorrhagic substance. Histological damage appears in many internal organs. The signs of toxicity vary somewhat for the various animals tested: Mice become drowsy and inactive initially with prostration, labored respiration, and convulsions occurring prior to death. The early signs in dogs are defecation and vomiting, followed by loss of muscle coordination, weakness, collapse, and death; drowsiness, which is a prominent early sign in most animals, is less noticeable in dogs.

The primary cause of death appears to be congestive heart failure. Autopsy of a mouse receiving a fatal intravenous injection of palytoxin reveals an extreme enlargement of the right, but not of the left, ventricle of the heart and accumulation of fluid in the lung, indicating a narrowing of the pulmonary vessels as the most probable cause of death. According to Pushkar Kaul at the University of Oklahoma, as little as 25 ng/kg injected into a dog can induce profound coronary vasoconstriction and produce an elevated T-wave in the electrocardiogram of the animal. At this dose the toxin induces intense cardiac muscle contractions that can lead to cardiac arrest. The contractions are associated with an increased uptake of calcium by the myocardial tissue.

Palytoxin is strongly irritating, in particular to the eye. When 100 to 400 ng/kg is instilled into rabbit eyes and not rinsed out, there is moderate tearing, swelling, edema, and conjunctivitis after four hours, which becomes severe within 24 hours. The conditions persist for at least a week. Irreversible ocular lesions occur at the higher dose level. When a rabbit's eyes are exposed to 5 micrograms of toxin per kilogram of bodyweight for 1 to 15 minutes before thorough rinsing, moderate to severe corneal damage appears within 24 hours.

Palytoxin is a universal cytolysin that is active against excitable and nonexcitable membranes. It is probably the most potent cytotoxic agent known. L. Beress and his associates at Kiel and Justus Liebig universities in Germany have found that palytoxin is a powerful hemolysin of the osmotic type, with an ED_{50} (the minimum effective dose for 50 percent of the animals tested) between 10 picograms and 2 nanograms per milliliter, depending on conditions. Cytolysis occurs slowly and is preceded by a large potassium loss. Erythrocytes that possess more sodium than potassium as intracellular cations are less sensitive to palytoxin. The toxin does not appear to be inactivated during hemolysis.

Medical Research Applications

There is little doubt that palytoxin will be an invaluable tool for medical and physiological research. It will be particularly useful for elucidating the complex biochemistry involved in diseases of the heart. Pharmacological studies indicate that palytoxin greatly perturbs the sodium, potassium, and calcium ion fluxes in cells. In a myocardial cell, an increase in the concentration of calcium ions is very harmful. The ions damage the mitochondria within the cell, halting the production of adenosine triphosphate (ATP). This in turn leads to loss of energy for contraction and relaxation of cardiac and smooth muscles. In addition, increased calcium uptake into a myocardial cell stimulates protease and phospholipase enzymes. The substances released by this stimulation cause massive damage to the ultrastructure of the membrane, resulting in lesions in the cell wall and, consequently, increased permeability of the cell to still more calcium ions from the surrounding interstitial fluid. The changes in the sodium and potassium levels, therefore, may be secondary effects — consequences of membrane damage caused by the increased calcium uptake by the cells.

The mechanism by which palytoxin causes this increased calcium uptake is unknown. One possible explanation is that the toxin binds to the calcium channel of the membrane in such a way that the channel gate remains open after contraction. If this is true, palytoxin could provide detailed information about the nature and structure of the calcium channel.

Palytoxin could also be useful in cancer research. Some cancerous cells appear to be very susceptible to the toxin, while others may be produced by it. Palytoxin completely cures Ehrlich ascites carcinoma in mice, for example, at doses as low as 5.3 ng/kg. However, its antineoplastic activity against P-388 lymphocytic mouse leukemia, a cancer cell commonly used in cancer research, is only marginal.

Hirota Fujiki and Takashi Sugimura, at Japan's National Cancer Center Research Institute in Tokyo, are currently evaluating palytoxin as a skin tumor promoter, and their preliminary results suggest that it may be active. Skin cancer proceeds in two major stages. In the first stage, the initiation stage, the carcinogen reacts irreversibly with the DNA of the cell. Initiation alone, however, will not produce a tumor. In the second stage, which is exceedingly complicated and not well understood, the initiated cell is transformed into a cell of a benign tumor, and finally into a cell of a malignant cancer, by a noncarcinogenic substance known as a tumor promoter. Unlike tumor initiation, which requires only a single contact with a carcinogen, tumor promotion requires repeated exposure to the promoter. All of the known tumor promoters are inflammatory agents that increase protease and phospholipase activities, two processes that require calcium ions. Thus palytoxin may promote tumors by increasing the flow of calcium ions to the initiated cell.

Whether palytoxin will have any practical use in medicine is uncertain at this time. Powerful toxins sometimes are useful at sublethal doses. Tubocurarine, for example, the active principle of one of the arrow poisons of South American natives, is used as a muscle relaxant. Other toxins, such as diphtheria toxin, seemingly have no value, and yet very recently it has been discovered that the toxic portion of the diphtheria toxin molecule has a potent antitumor activity when this portion is covalently bonded to an immunoglobulin. Diphtheria toxin by itself has no anticancer activity. Could the anticancer activity of the palytoxin molecule be enhanced by attaching it to an immunoglobulin? Further research is needed before we will know if this enigmatic extract from the legendary *limu-make-o-Hana* proves beneficial to humankind.

Richard E. Moore is a Professor of Chemistry at the University of Hawaii in Honolulu. Philip Helfrich is Director of the Hawaii Institute of Marine Biology. Gregory M. L. Patterson is a biologist in the Chemistry Department of the University of Hawaii.

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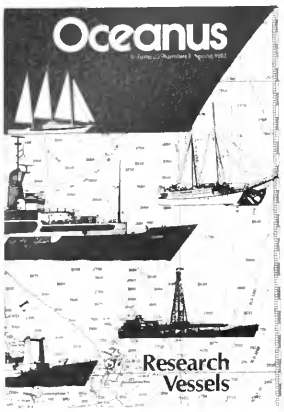

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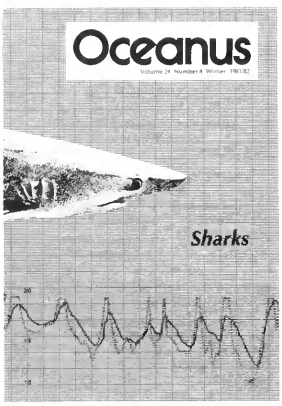


Research Vessels, Vol. 25:1, Spring 1982 — Despite rising costs, ships continue to play a key role in marine science. An article on the United States university fleet is followed by an argument for the construction of more semisubmerged ships, a history of the submersible, and a look at a submersible system of the future. Two articles advocate a return to sails, while another profiles a famous drilling ship. The human side of oceanography is also portrayed.

Sharks, Vol. 24:4, Winter 1981/82 — Shark species are more diverse and less aggressive than the "Jaws" image leads us to believe. Along with several informative articles on shark physiology, this issue discusses aggression, grouping, and the prospects for a new shark repellent. Also included: advice to swimmers, divers, and victims.

Oceanography from Space, Vol. 24:3, Fall 1981 — Satellites already provide useful data and are likely to make important future contributions toward our understanding of the sea. This issue discusses their use in mapping wind patterns, chlorophyll concentration, sea ice movement, changes in climate, and sea-surface topography. The workings of a typical satellite are explained, as are some commercial applications of this new technology.

General Issue, Vol. 24:2, Summer 1981—A wide variety of subjects is presented here, including the U.S. oceanographic experience in China, ventilation of aquatic plants, seabirds at sea, the origin of petroleum, the Panamanian sea-level canal, oil and gas exploration in the Gulf of Mexico, and the links between oceanography and prehistoric archaeology.

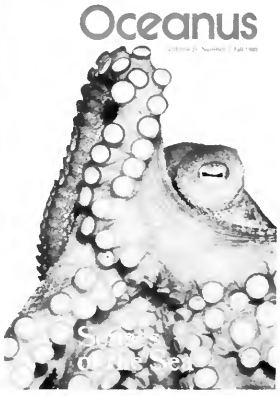
The Oceans as Waste Space?, Vol. 24:1, Spring 1981 — *Limited supply only.*

The Coast, Vol. 23:4, Winter 1980/81—Celebrating the Year of the Coast, this issue is dedicated to the more than 80,000 miles of our nation's shorelines. Included are articles on barrier islands (federal policies and hazard mapping), storms and shoreline hazards, off-road vehicles on Cape Cod, the Apalachicola experiment, and coastal resource conservation and management.

Senses of the Sea, Vol. 23:3, Fall 1980—Marine animals have complex sensory systems. Here we learn that lobsters can taste and smell, bacteria can sense their world magnetically, and some fish can sense electrically. We discover that octopuses have a sophisticated sense of equilibrium, and that some insects use the water surface to communicate. Underwater vision, hearing, and echolocation are also discussed.

General Issue, Vol. 23:2, Summer 1980—A collection of articles on a range of topics, including: the dynamics of plankton distribution; submarine hydrothermal ore deposits; legal issues involved in drilling for oil on Georges Bank; and the study of hair-like cilia in marine organisms.

A Decade of Big Ocean Science, Vol. 23:1, Spring 1980—As it has in other major branches of research, big science has become a powerful force in oceanography. The International Decade of Ocean Exploration is the case study. Eight articles examine scientific advances, management problems, political negotiations, and the attitudes of oceanographers toward the team approach.



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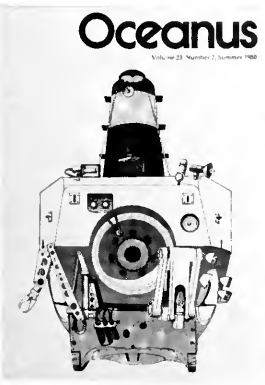

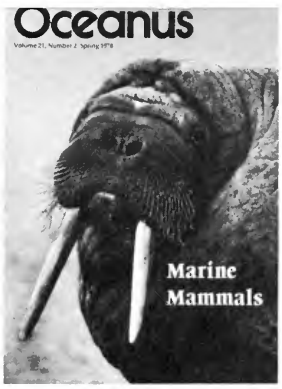

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Ocean Energy, Vol. 22:4, Winter 1979/80—How much new energy can the oceans supply as conventional resources diminish? The authors in this issue say a great deal, but that most options—thermal and salinity gradients, currents, wind, waves, biomass, and tides—are long-term prospects with important social ramifications.

Ocean/Continent Boundaries, Vol. 22:3, Fall 1979—Continental margins are no longer being studied for plate tectonics data alone, but are being analyzed in terms of oil and gas prospects. Articles deal with present hydrocarbon assessments, ancient sea-level changes that bear on petroleum formations, and a close-up of the geology of the North Atlantic, a current frontier of hydrocarbon exploration. Other topics include ophiolites, subduction zones, earthquakes, and the formation of a new ocean, the Red Sea.

General Issue, Vol. 22:2, Summer 1979 — *Limited supply only.*

Harvesting the Sea, Vol. 22:1, Spring 1979 — *Limited supply only.*

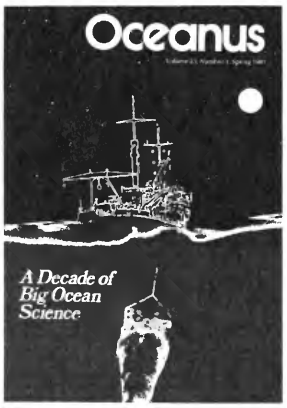
Oceans and Climate, Vol. 21:4, Fall 1978 — *Limited supply only.*

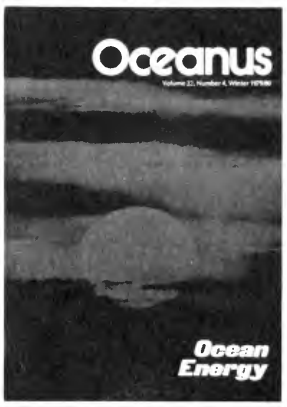
General Issue, Vol. 21:3, Summer 1978—The lead article looks at the future of deep-ocean drilling, which is at a critical juncture in its development. Another piece—heavily illustrated with sharp, clear micrographs—describes the role of the scanning electron microscope in marine science. Rounding out the issue are articles on helium isotopes, seagrasses, red tide and paralytic shellfish poisoning, and the green sea turtle of the Cayman Islands.

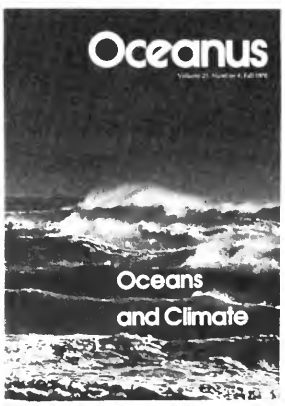
Marine Mammals, Vol. 21:2, Spring 1978—Attitudes toward marine mammals are changing worldwide. This phenomenon is appraised in the issue along with articles on the bowhead whale, the sea otter's interaction with man, behavioral aspects of the tuna/porpoise problem, strandings, a radio tag for big whales, and strategies for protecting habitats.

Sound in the Sea, Vol. 20:2, Spring 1977 — Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines.

The Deep Sea, Vol. 21:1, Winter 1978—Over the last decade, scientists have become increasingly interested in the deep waters and sediments of the abyss. Articles in this issue discuss manganese nodules, the rain of particles from surface waters, sediment transport, population dynamics, mixing of sediments by organisms, deep-sea microbiology—and the possible threat to freedom of this kind of research posed by international negotiations.







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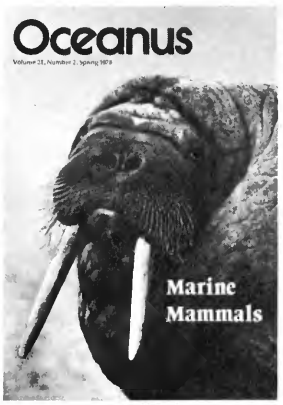

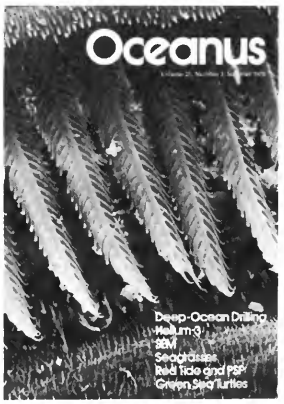

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